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Joint analysis of resident complaints, meteorological, acoustic, and ground motion data to establish a robust annoyance evaluation of wind turbine emissions

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ABSTRACT

In order to advance the expansion of onshore wind energy, wind turbines (WTs) must be erected in often complex terrain. The orography and the associated meteorological conditions, as well as the complex propagation of sound and ground motion waves can lead to increased annoyance of residents.

Here a joint investigation of residential noise reports, meteorological, acoustic and ground motion data together with operational parameters of a wind farm in southern Germany is presented, with the objective to assess the annoyance of residents affected by WT emissions. Once strongly annoyed residents had been identified, simultaneous measurements were conducted over a 2-month period while residents used a noise reporting app to document their annoyance. A combination of the data shows that WT-related signals can be detected by acoustic and ground motion measurements in the vicinity of the WTs and, to a lesser extent, at the residential sites. In addition, background noise can be identified well. The app data indicates higher complaint rates in the early morning, evening and night hours. Changes in rotation rate seem to be the cause of annoyance as well as high rotation rates. These findings can be used to adjust WT operation in order to decrease immissions.

1. Introduction

1.1. State of the art

Wind energy is an important energy source for moving away from coal and other fossil fuels. Nevertheless, there has been a decelerating trend in the installation of wind turbines (WTs) in Germany in recent years. After more than 5 GW of annually installed capacity was achieved in 2017 through new projects and repowering, the expansion of wind energy in Germany fell to under 1 GW in the first half of 2021 [1]. Reasons for this are slow approval procedures for WTs and complaints by nearby communities. For 20% of the wind farm projects in Germany these conflicts have to be settled in court [2]. Beside visual aspects, also aspects such as acoustic and vibrational disturbances by WTs are expected to lead to a negative perception of WTs [3,4].

While the percentage of strongly annoyed residents in the vicinity of wind farms is expected to be low, the ones affected experience negative effects like sleeping problems or lack of concentration (e.g. Refs. [5–8]). One method to investigate these negative effects of WTs on residents is an epidemiological study design. Therein it is investigated, whether stress related diseases, e.g. cardiovascular diseases or diabetes, occur more often in the proximity of WTs [9–12]. Despite being valuable contributions to the understanding of stress effects by WTs, these investigations do not allow conclusions (a) about less serious stress effects, (b) which circumstances exactly result in symptoms, and (c) which measures

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can be taken to reduce annoyance and the associated stress effects. Another methodological approach consists of laboratory studies. These are mainly applied in order to investigate acoustic characteristics of WT sound that can be linked for example to annoyance and sleep disturbance [13–16]. However, everyday circumstances, including weather conditions, sleeping situation or geographical location, as well as the process of the wind farm planning, construction and economic participation of residents are not considered. For mitigation measures, it is important to understand exactly which factors lead to annoyance.

Research in the field of wind turbine acoustics has been ongoing for 40 years [17]. For almost the same period of time, studies have been conducted to investigate annoyance due to low frequency sound from WTs [4]. Multiple mechanisms lead to generation of sound with either aerodynamic or mechanical origin, with broadband or tonal character in the low- and mid frequency range. The expansion of wind energy on land leads to more reported annoyance, as a growing number of people live closer to WTs [4]. In many cases, it is argued that low frequency (20–200 Hz) and infrasonic (1–20 Hz) sound of WTs is perceptible even at large distances. Because of the long wavelength of low frequency and infrasonic sound, the attenuation rate with distance is lower compared to sound in the higher frequency range. Furthermore, building facades, which have a lower sound reduction index in the low frequency range promote the propagation of low frequency sound into buildings. According to Refs. [18,19], infrasonic sound pressure is below the human hearing threshold and high levels (124-71 dB for the frequency range 1.6–20 Hz [18,20]) are necessary to be within the audible range, whereas sensitive people could perceive infrasound even at lower levels [17]. Several studies describe the coupling of infrasound with the building structure, which can lead to detectable effects in the interior [21,22]. In order to identify WT induced sound at residential buildings, simultaneous acoustic measurements both in the area of the WTs and at the residents' homes are necessary. Additionally, the sound propagation from WTs to residential buildings is influenced by many factors. In Ref. [23] especially refraction, atmospheric absorption and scattering by turbulence are mentioned as significant factors influencing sound propagation. In noise prediction models, such as the international standard [24], noise levels are calculated for worst case atmospheric conditions. There are uncertainties related to WT noise, e.g., multiple reflections are not taken into account. Therefore, work is being done on more accurate models that include topographic and meteorological effects [17,25–27]. [27] argue, that more accurate prediction models can improve noise reduction measures and, thus, also the acceptance among the population.

Furthermore, meteorological factors can influence the perceptibility of WT sound at greater distances. Here, atmospheric conditions, especially atmospheric stability determined with the Monin–Obukhov length L giving the height of the stable boundary layer [28] and corresponding parameters like wind shear exponent and temperature gradient, should be mentioned. The local wind conditions do not only affect the power output of the wind farm but also influence the WT sound generation. In several studies [29,30] it was shown that stable atmospheric conditions have effects on WT sound and its propagation. Atmospheric stability leads to low wind speeds at ground level and thus to low ambient noise, whereas high wind speeds at hub height lead to high WT speeds and thus higher sound pressure levels [29]. Furthermore, it was found that measured low frequency sound in residential buildings is more pronounced during stable conditions [30,31].

In addition to airborne sound pressure waves, WTs induce elastic waves due to the coupling of their foundation with the ground [32]. These ground motions cause recordable signals and have been the subject of many seismological studies in recent years [33–39]. Although these vibrations are mostly very weak and not perceptible by humans, they can disturb high-precision measurements, e.g. ground motion monitoring networks [34,36–39]. Therefore, WT-induced ground motions are studied extensively. Natural vibrations of WTs are related to the eigen modes of the WT tower and blades [32,40], and the blade-passing frequency (BPF) and its multiples (e.g., Refs. [32,34,41]). While the latter are proportional in frequency to the rotation rate of the WT, natural vibrations are of constant frequency but increase in amplitude with faster rotation. Typically they occur at frequencies below 20 Hz. Lower frequency modes are attenuated less than higher frequencies with distance and can be detected up to distances of more than 10 km (e.g., Refs. [33,35]). Modelling of WT related ground motion propagation can be studied analytically for homogeneous subsurfaces [42] or by the application of finite-element modelling for arbitrary subsurface (e.g., Ref. [43]), but is beyond the scope of this paper. In surveys of residents living in the vicinity of wind farms vibrations have been named as a disturbing property of WT operation (e.g., Ref. [44]). Therefore, ground motion measurements are performed in addition to the acoustic measurements in this study. In Germany the effect of vibrations on humans in buildings is defined in Ref. [45] for residential sites. The frequency range relevant for human sensitivity to vibrations is 1–80 Hz, with signals below 5.6 Hz damped by the application of a filter in the evaluation. A value of ~0.1 mm/s is widely regarded as a lower limit for perceptible signals.

Since WT operation is variable and influences a resident's annoyance, long-term acoustic measurements with simultaneous recording of meteorological, ground motion and WT-operational data are required. As stated by Ref. [4], linking this data with self-reported annoyance might be helpful to better understand the reasons for annoyance.

In recent years a number of studies were conducted that combine objective with subjective measures. [46] did measurements of acoustics and vibrations inside and outside residential buildings close to a wind farm. The residents, who had lodged complaints concerning the wind farm, provided diary observations. Access to internal data and shut down time periods enabled the assignment of measurement data to turbines and the measurement of background emissions. The study was carefully designed and set a good example for subsequent research. Since the hub height of the investigated WTs is 69 m, which is below today's standard, the results could differ considerably for today's WTs, which are often twice as high, with regard to ground vibrations and sound propagation. [47] also provided participants with a pen-paper noise diary while simultaneously recording sound pressure levels inside and outside their homes. Additionally, they measured wind speed and wind direction at the location. They found an effect of sound pressure levels, prevalence of amplitude modulation, and WT power output on high annoyance. Since only two residents were involved in the study, future studies would need to be conducted with larger samples to generalize the results. In addition, mitigation measures and the detection of situations when they should apply might depend on a more detailed analysis of further parameters, such as the above mentioned weather conditions.

[48] used a smartphone app that allowed participants to assess the noise situation every day over five weeks from a fixed location. Sound immissions at each participant were calculated using sound power levels of each turbine type, simulated meteorological data, and WT operation data. A relationship between annoyance and increasing sound pressure levels was identified. This study included a large number of participants (68 individuals) who were not selected based on their level of annoyance. A regular use of the app with and without annoyance may improve the attribution to

WT data. However, participants were placed in an artificial situation by fixed locations. Spontaneous annoyance responses, which are of essence in a real life scenario, were most likely not covered with this approach. Within the project TremAc [49,50] acoustic, ground motion and meteorological measurements were carried out simultaneously to find thresholds for an objective assessment of turbine sound and vibration emissions taking into account turbine design, topography and distance from the place of immission. Additional interviews with residents were conducted but not synchronous to the measurements. Thus, no direct link between factors influencing annoyance and WT operation could be established.

1.2. New interdisciplinary study

The aim of this study is to present the foundation for an analysis of noise annoyance which allows to give recommendations for mitigation measures. For that purpose, it is not only necessary to understand possible stress effects of WT noise exposure, but also investigate the interrelation of various physical parameters of noise occurrences. As a follow-up study to TremAc [49], the basis of the investigation is the residents' perception and their subjective evaluation of the noise, while integrating them with acoustic, ground motion and meteorological measurements. Similar to Refs. [46,47], measurements are carried out inside and outside residential buildings, capturing the circumstances of the residents' everyday lives. Residents' evaluations are recorded in parallel with the measurements and therefore allow for precise overlap of these data and to analyze the exact moments of annoyance. Similar to Ref. [48] this is achieved by handing out an app to the participants, which they are allowed, though, to use flexibly in any situation of their routines. The sites of strongly annoyed residents were selected for the measurements, so that they are done at the most sensitive locations. The focus on the subgroup of strongly annoyed residents does not allow for generalization for all residents of a wind farm but (a) gathers meaningful information on those who are, in fact, negatively affected, and (b) promises to extract the circumstances of annoyance with more clarity as annoyance occurs more often and is experienced more strongly. While the measurements are conducted at selected residential buildings, annoyance periods are documented via the app from a larger sample of persons living in the vicinity of the wind farm.

This study was conducted in southern Germany in the municipalities of Kuchen and Geislingen an der Steige on the Swabian Alb at wind farm Tegelberg (Fig. 3). The location was chosen because the research team learned through local authorities about conflicts concerning the wind farm. Additionally, the geographical location in mid-range mountains adds to the research interest, as the impact of such a topography on sound and vibration propagation is not well researched. Shielding by the surrounding mountains leads to reduced wind-induced ambient noise, thus residents in valley locations might increasingly perceive WT sound [29,51].

The considered wind farm is located at the top of the escarpment of the Swabian Alb and consists of three WTs (hub height 139 m, rotor diameter 120 m, 2.78 MW rated power). The maximum rotational speed of this WT type is 12.5 rotations per minute (rpm) at full load. The average difference in height between the rotors and the town is about 400 m, and the average distance approximately 1 km. Operational data of the wind farm was provided by the wind farm operator and shut down periods during the night allowed to clearly distinguish WT sounds from background emissions. At the onset of the investigation the wind farm was in operation for two years and seven months.

The main objective of this paper is to describe the interdisciplinary approach for the evaluation of annoyance together with acoustics, ground motion and meteorological measurements. In a first step, people in the vicinity of the wind farm were interviewed and strongly annoyed people were identified. Simultaneous and time-synchronous measurements together with documentation of periods of high annoyance were implemented to provide the foundation for the noise report evaluation.

The paper is structured as follows: Section 2 explains the procedure of the resident surveys and Section 3 describes the meteorological, acoustic and ground motion measurements carried out in the vicinity of the wind farm. Section 4 shows how the different kinds of data can be merged and how they complement each other. Section 5 analyzes and discusses the results obtained and, finally, Section 6 presents the main conclusions.

2. Resident survey

To assess WT noise annoyance, as a first step, a resident survey was conducted. Its goals were to understand how residents perceive the WT and their emissions. The survey built a basis for further measurements, because its results identified residents, who experience annoyance, and therefore places where measurements were most critical.

2.1. Recruitment

In order to recruit participants for the survey, information about the project was disseminated via press releases and announcements by local authorities. 1570 addresses were randomly collected from public phone directories within a 5 km radius around wind farm Tegelberg. The residents were contacted from July to September 2020 via letter and a few days later via phone call. Additionally, residents were allowed to directly contact the research team and were included in the sample. This was done to increase acceptance of the study in the community. The participants were interviewed along a standardized questionnaire via telephone by trained students.

2.2. Questionnaire

The survey questionnaire included 311 items adopted from previous studies on stress effects of WT emissions [7,52,53]. It assesses stress indicators concerning WT emissions, especially due to noise annoyance and low frequency noise. These stress indicators include somatic and psychological symptoms associated with WT emissions. Furthermore, the questionnaire covers cognitive and behavioral coping responses, and a range of moderators, as for example attitude towards wind energy in general and towards the local wind farm, perception of the planning process, and general health indicators.

2.3. Noise report app

In addition to the survey an app was developed that allowed users to report when they were annoyed by WT noise. The web survey tool Unipark (Tivian XI GmbH) was used to design the app as an online questionnaire. Participants could access it via an URL link. The app was constantly available to residents that participated in the survey, so that they could report noise occurrences immediately at any time. Usage of the app was enabled simultaneously to acoustic, ground motion and meteorological measurements, which allowed for data analysis at times when residents made noise reports.

Participants were asked during the interviews whether they wanted to use the app. In the app they were asked (a) the time of the noise, (b) how much they were annoyed by it (on a scale from 0 “not at all” to 4 “very”), (c) during which activity they were disturbed, (d) what the noise sounded like, (e) how much they were troubled by any physical and mental complaints on that day (from 0 "not at all" to 4 "very"), (f) whether they had specific thoughts or feelings when they heard the noise, and (g) if they took any measures to cope with the noise.

2.4. Results

2.4.1. Sample characteristics

In the survey, 148 residents of the wind farm Tegelberg were recruited. The sample was in large parts male (68.6%), with a mean (M) age of 62.55 years (standard deviation, SD = 11.72, range = 24–83 years). With 47% almost half of the participants were retired and 45.6% were working – either employed, self-employed or as public servant. The majority owned property (93.6%) and lived in their homes on average for 32.08 years (SD = 16.34). On average, they lived in households of 2.42 persons. None of the participants received financial benefits from the local wind farm or was working in the wind energy industry.

2.4.2. App usage

The app was first distributed on 2020-08-08 via a link sent by e-mail to 46 participants, who agreed to use it. As displayed in Fig. 1, these participants had a higher level of noise annoyance (M = 3.05, SD = 0.96) compared to the participants who did not want to use the app (M = 1.44, SD = 1.39, large effect size). Of these participants, 33 (71.7%) were strongly annoyed (see Section 2.5). This indicates that predominantly those who regularly experience WT noise annoyance used the app. Furthermore, 23.9% of the app users said that they have been in active opposition to the wind farm in the past (e.g. joining an action group, writing a letter to a news outlet or someone involved in the planning, and similar activities) and additional 15.2% were opposed but did not become active. Yet, the app was not only used by opponents as 37% were supporters of the wind farm (34.8% passive, 2.2% active).

For this publication, data until 2021-02-04 were analyzed. During that time 431 noise reports were made by 17 users. The majority of the reports is related to the evening, night and morning hours, with only 13.1% of the reports being made between 10:00 local time (09:00 UTC) and 18:00 local time (17:00 UTC). Accordingly, 51.5% reported to have been disturbed while sleeping or while falling asleep (see Fig. 2). 71.9% of the noise occurrences were perceived while being inside, 23.7% outside the house. On average users felt moderately annoyed (M = 2.84, SD = 0.91). They mostly did nothing in reaction to the noise (27.1%), closed windows or doors (20.3%), or moved to another location (17.6%). A variety of cognitive and affective responses was described, the most prevalent were feelings of anger and stress (18.7%), discomfort and disquiet (10%) and thoughts in the line of "there they are again" (8.9%).

2.5. Identifying households for acoustic and ground motion measurements

In order to develop a better understanding of why some residents are annoyed by WT sound immissions, acoustic and ground motion measurements were conducted in households with strongly annoyed residents. One goal of the survey was to identify such residents. In accordance with the definition of [6,7] a person is understood to be "strongly annoyed" when they express to be at least somewhat annoyed (scale point 2) by WT noise and experience at least one somatic or psychological symptom associated with WT noise at least once per month. In the sample 33.1% fit that description. If a participant agreed to have measurements undertaken in their home and also used the noise report app, they were short-listed for measurements. Eleven households came into consideration.

Next, these eleven households were evaluated with regard to their location. They were preferred to be located in the northeast of the municipality of Kuchen, so as to be both close to the WTs, and the profiling lidar and scanning lidar (see Section 3.1). In order to have low background noise from the surroundings, proximity to streets with a lot of traffic was avoided. Unfortunately, the area, which was reported to be affected the most by the WTs, is largely located close to railway tracks. The impact of passing trains was judged to be manageable for sound measurements, as timetables for the trains were available and parts of the area were shielded from the tracks by a noise barrier. It was, therefore, decided to also include residents with railway tracks nearby. Pre-existing annoyance due to these noise sources among strongly annoyed residents was low: they were only slightly annoyed by traffic noise (M = 0.82, SD = 1.09) as well as train traffic (M = 1.33, SD = 1.46). During the interviews it was often mentioned that they lived with the sounds from trains for decades and got used to it. In the end, four residents were chosen, who met the aforementioned requirements and had enough space inside and outside their houses for the measurement instruments.

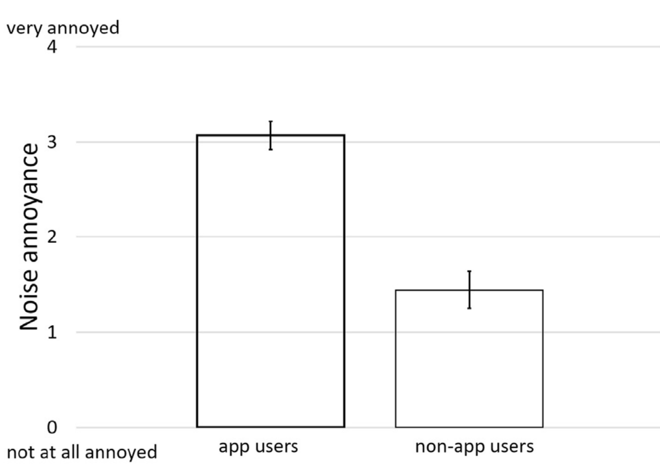

Fig. 1. Wind turbine noise annoyance of residents, who wanted to use the noise report app, and those, who did not. Error bars indicate the standard error of the mean. The difference is significant with $t(90.31) = 6.715$, $p < 0.001$, $d = 1.34$.

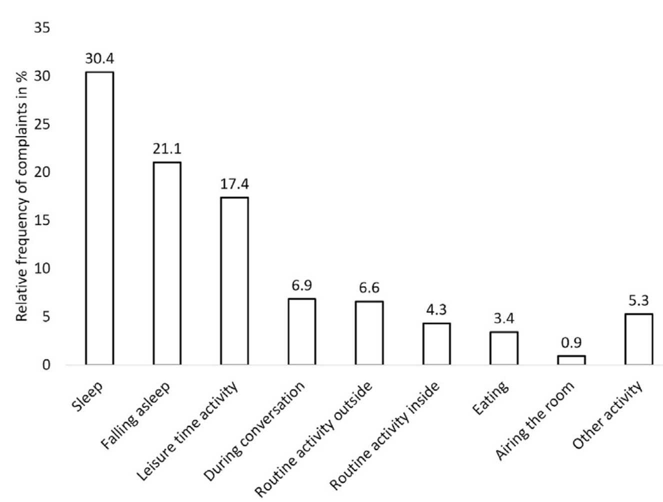

Fig. 2. Activity at the time of complaint.

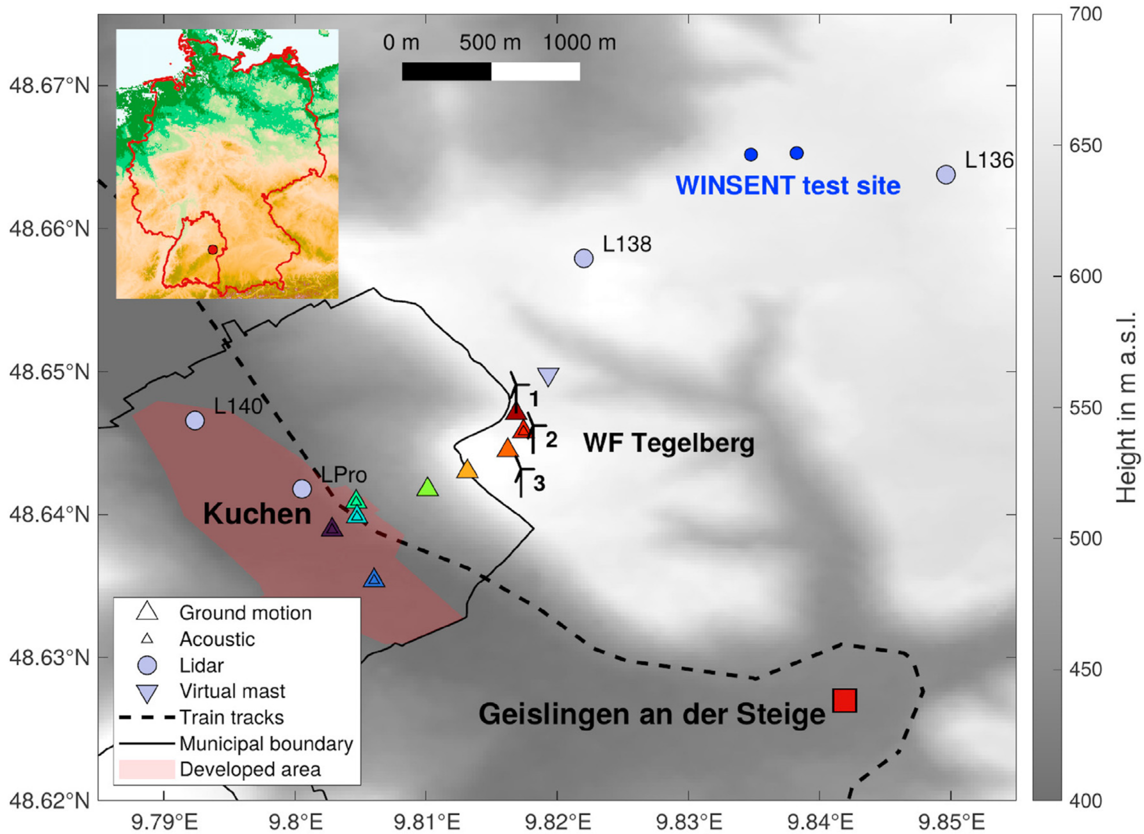

Fig. 3. Topographic map of the town of Kuchen and its surroundings with locations of the wind turbines of wind farm Tegelberg, lidar, acoustic, and ground motion recording instruments. The blue circles mark the location of the meteorological masts at the WINSENT test site. The inset shows the location of the measurement area within Germany and the state of Baden-Württemberg (red outlines).

2.5.1. Exemplary resident

In order to exemplify how the data from the survey and the app can be integrated to gain a better understanding of the environmental conditions in which noise annoyance occurs, the case file of one exemplary resident is described in more detail:

In the interview the resident describes a typical situation in which they are annoyed by WT noise to be during the night. They describe the WTs to sound like gearing sounds (like a badly oiled engine) or aircraft sounds and find the words booming, droning, humming, swooshing, squeaking and growling to be adequate. All the while, it is a recurring, periodic sound. In this typical situation they are in their bedroom or bathroom which are located on the side of the house facing the WTs and from which they can also see them. They perceive the sounds to be amplified by reflecting from the walls of their neighbour's house, while they ascribe the roofing an insulating effect. The sounds are reported to be heard especially well in downwind but also upwind direction relative to the WTs. When they notice higher wind speeds they describe the sounds to be very loud, during lower wind speeds they can hear gearing sounds. In reaction to the noise they tend to close the windows.

The resident submitted 94 noise reports through the app. The vast majority of the reports occurred during the night (41.48% between 22:00 and 01:00 UTC) and early morning hours (24.47% between 04:00 and 06:00 UTC) and while being inside (92.55%). Accordingly, they were mostly disturbed when they tried to fall asleep (37.23%) or when they were sleeping (38.3%). 18.09% of the noise complaints pertained to other leisure activities. On average, they were moderately annoyed ($M = 2.97$, $SD = 0.62$). The sounds were described to resemble aircraft (54.26%) or gearing sounds (44.68%). The most common reaction was to close the window (57.45%), with checking the clock coming second (17.02%), and getting up coming third (9.57%).

3. Measurements

Measurements were conducted in the municipality of Kuchen close to the wind farm Tegelberg, with the goal of quantifying meteorological, acoustic and ground motion parameters. Fig. 3 shows a map of the town Kuchen indicating the locations of the three WTs and the locations of all measuring instruments. WT 1 (hub height in 809 m above sea level (a.s.l.)) was chosen for the acoustic and ground motion measurements, as it is located in a field. This allowed measurements at a greater distance of approximately 140 m from the WT and thus a more holistic measurement of the turbine. WT 2 (hub height in 831 m a.s.l.) and WT 3 (hub height in 828 m a.s.l.) are located in the forest. Measurements at these WTs would only have been possible on the crane site below the turbine. For the acoustic measurements, the location near WT 1 was also considered more appropriate due to lower background noise from trees. Long-term surveillance was carried out for about 54 days of acoustic (by University Stuttgart - Stuttgart Wind Energy (SWE)) and 106 days of ground motion (by Karlsruhe Institute of Technology - Geophysical Institute (GPI)) measurements. The Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW)) captured about 113 days of wind lidar profiler measurements to extend the long term meteorological measurements at the WINSENT wind energy test site [54] nearby the wind farm. The periods of the measurements can be found in Table 1. The

Table 1
Measurement periods at the wind farm.

Measurement category	Start	Stop
Wind profiler	2020-10-16	2021-02-08
Acoustic	2020-10-22	2020-12-16
Ground motion	2020-10-20	2021-02-05

Table 2
Measurement periods at residential sites.

Site	Start	Stop
Resident 1	2020-10-21	2020-11-09
Resident 2	2020-11-09	2020-11-23
Resident 3	2020-11-23	2020-12-07
Resident 4	2020-12-07	2020-12-16

instruments at the residential sites (acoustic and ground motions) were recording for approximately two weeks at each site (see Table 2).

During the measurement periods the WTs were shut down regularly during nighttime. This allows to assign acoustic and ground motion signals to the WT operation. Between 2020-11-01 and 2020-11-30 all WTs were shut down at 00:00, 03:00, 18:00 and 21:00 UTC for 20 min. From 2020-12-05 to 2020-12-11 the shut down was reduced to the time periods at 00:00 and 03:00 UTC. Additionally, gradual shut down was implemented by the wind farm manager during six nights to separate the signals and assign them to the single WTs.

In the following, the ground motion, acoustic and meteorological measurements are described in detail, with information about the campaign instrumentation and the applied data analysis. Data from 2020-12-05 is used for comparison of the different methods.

3.1. Meteorology

3.1.1. Instrumentation

In-situ meteorological measurements are provided by the wind-energy research test site WINSENT, which is located at 665 m a.s.l. and about 2.4 km north-west of the wind farm Tegelberg (see Fig. 3). Since 2018 two meteorological masts with a total height of 100 m each capture meteorological data. They are equipped with various instruments to measure wind speed and direction, air temperature, air humidity, air pressure and precipitation at different heights. Several remote sensing devices such as two Doppler wind lidars (L136 and L138) and a ceilometer are installed in the vicinity of the test site. One profiling lidar device (LPro) was used to record wind profiles using a 6-Beam profiling algorithm. It was installed in the valley close to the town Kuchen, 1.2 km westerly from the wind farm. These derived profiles are supplemented by planar scans from the third autonomous scanning lidar positioned 1.8 km westerly from the wind farm in the valley, too. For supplementary analysis lidar measurements provide wind profiles at the plateau near the turbines of the wind farm Tegelberg as well as in Kuchen. Furthermore, areal lidar scans complement the results with 2D sections of the wind flows to qualitatively describe and evaluate the situations. The analysis of the data derived from the three profiling and scanning lidars is outside of the scope of this paper.

3.1.2. Data analysis

The data collected at the meteorological masts of the WINSENT site are filtered according to appropriate plausibility criteria and stored as 10-min averages. The recorded wind direction is additionally filtered based on the valid sectors, since the mast structure has an influence on the signal. With the complex orography around the wind farm and the WINSENT test site the transfer of insights gained from measured data have to be carefully verified. In Fig. 4 the SCADA (Supervisory Control and Data Acquisition) data captured by WT 3 is correlated with meteorological data measured at the WINSENT test site.

In Fig. 4a it is clearly visible that the wind speed measured by WT 3 at hub height does not correlate perfectly with the wind speed measured at the WINSENT test site. Two circumstances have an effect here, on the one hand the different measuring heights lead to higher wind speeds at hub height of the turbine, assuming a logarithmic wind profile. On the other hand local blockage effects by the rotor blade roots and nacelle structure interfere with the wind speed measurement at the turbine nacelle. The yaw alignment of the WT follows the wind direction measured at the test site (see Fig. 4b). Some minor misalignment towards higher yaw angles can be observed for southerly wind directions (150°–250°). For westerly wind directions the turbine has a tendency to yaw slightly to the left. These deviations between the measured wind direction at the test site and the yaw angle of the WT are introduced by the orographic differences in the upwind direction of both locations. In Fig. 4c the temperature measured at the WINSENT test site is compared to the temperature at hub height as reported by the SCADA system of the WT. The observed deviations can partially be explained with the different measuring heights (temperature

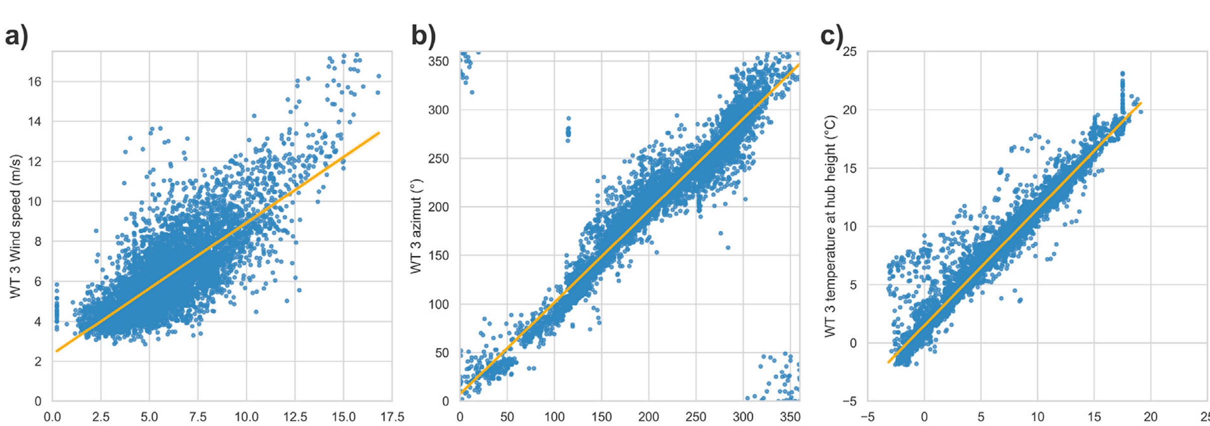

Fig. 4. Correlation of a) wind speed, b) wind direction and c) temperature captured at the WINSENT test site and SCADA data from WT 3. Data points were the turbine was not operating or reported non-normal state are excluded.

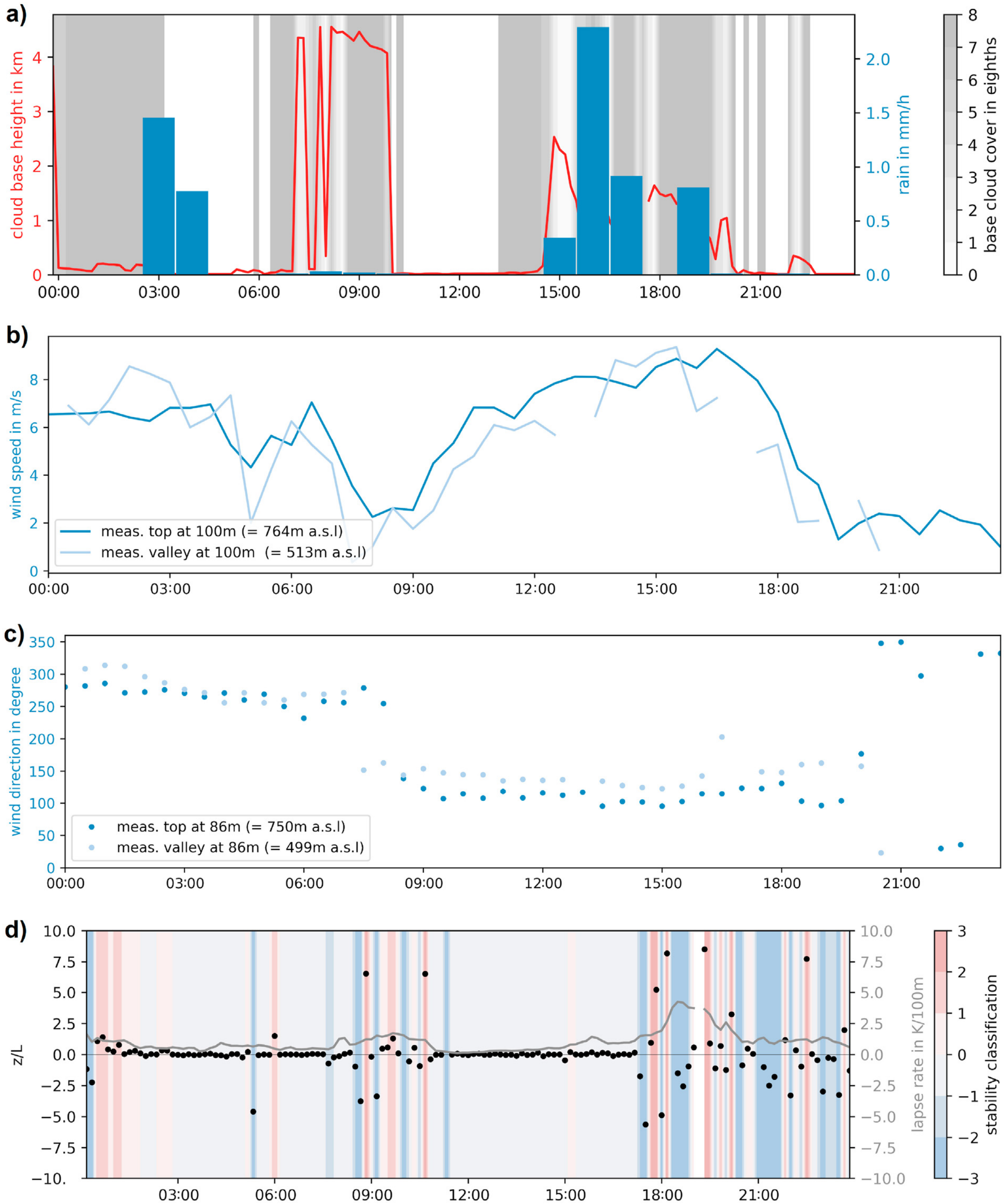

Fig. 5. Data example of meteorological data for a 24-h time window at 2020-12-05 from the wind energy research test site WINSENT. a) cloud base height (red line) and base cloud cover (gray shading) with rain (blue columns), b) wind speed at different heights (blue lines), c) wind direction at different heights (blue dots), and d) atmospheric stability (black dots), stability classification (blue to red shading) with lapse rate (gray line).

measurement at WT 3 hub height in 828 m a.s.l. versus sensor at WINSENT test site at 751 m a.s.l.) depending on the temperature gradient in the lower atmospheric boundary layer. Nevertheless, the use of an uncalibrated sensor on WT 3 for temperature measurement is the main reason for the small deviation. On average, this leads to a 2 °C higher temperature at WT 3.

The lidar data presented in this paper are from a profiling lidar installed in the valley close to Kuchen. This laser-optical measuring system allows the time-synchronous recording of wind speed and wind direction between 50 m and over 500 m above ground by the use of a six beam profiling algorithm [55]. This makes it possible to investigate whether the wind speed changes with increasing altitude, which allows statements about the wind profile. The wind profile can vary depending on the wind and weather conditions and is influenced by the location of the measuring system in the valley and the orography at the site. In addition to changes in wind speed, the wind direction can also change with increasing altitude, the so-called veer. This is also influenced by the orography, but also by thermal effects and Coriolis forces. Depending on the weather conditions, it is even possible that the wind blows from two different directions at different heights. The data of the lidar system are determined with a temporal resolution of 5 min over the entire measurement period. A comparison between wind speed and direction measured at the WINSENT test site at the same heights above ground are shown in Fig. 5b and c. It can be concluded that the meteorological conditions at the wind farm are comparable to those at the WINSENT test site.

In addition, the atmospheric stability prevailing in the vicinity of the WINSENT site can also be transferred to the site of wind farm Tegelberg. The atmospheric stability can be determined with the help of the collected measurement data of the meteorological mast and represents a further criterion to be able to assign the joint data - in particular those of the collected sound measurement data (see Chapter 3.2). The atmospheric stability can be described by a variety of parameters. In general a distinction is made between static, dynamic or thermal stability. As the investigated area is located in complex terrain, the dynamic stability is considered. The evaluated quantities are based on different input measurements and allow for an additional perspective on the atmospheric conditions. These stability parameter can only be determined using measurements at various heights. Therefore it is required to use the data from the WINSENT test site as meteorological measurements are not conducted in such detail at the wind farm.

In the literature, the ratio of height above ground z to the Obukhov length L [56] is used to describe atmospheric stability. This ratio is called ζ and is calculated by

$$\zeta = \frac{z}{L}$$

$$L = -\frac{u_*^3\overline{\Theta_v}}{\kappa g(\overline{w'\Theta_v'})}$$

where

z	height above ground
L	Obukhov length
u_*	friction velocity
Θ_v	potential, virtual temperature
κ	von Kármán constant: $\kappa = 0.4$
g	gravitational acceleration: $g = 9.81$ m/s^2
w	vertical wind component

For $L < 0$, the surface layer is statically unstable, whereas for $L > 0$ it is statically stable. Under neutral conditions, the ratio ζ goes to 0 as the Obukhov length L goes to ∞.

Like z/L, the Bulk Richardson Number Ri_B describes the dynamic stability. For neutral z/L, the scatter in Ri_B is particularly small. The mean value is around 0. Thus, for neutral conditions, Ri_B and z/L agree well. The scatter in Ri_B increases with increasing stability and convectivity. The trend is observed that Ri_B increases with increasing z/L and thus detects the same stabilities as z/L on average.

The wind shear coefficient α also describes the dynamic stability. α is significantly higher in situations with $z/L > 0$ than in convective situations with $z/L < 0$. However, no continuous increase of α with increasing stability from z/L can be observed. In neutral situations, α also varies strongly. The values are similar to those of α in conditions that tend to be more stable. α is thus less suitable for estimating stability for the complex site. In the following the ratio z/L is used to describe the dynamic stability in the atmosphere.

In order to be able to evaluate the collected meteorological data later on with the data of the research partners, the data should be

Table 3
Technical data of the acoustic measuring instrument for inside measurements used by SWE.

Manufacturer	Brüel&Kjaer
Type of capsule	4964
Sensitivity	50 mV/Pa
Frequency range (±3 dB)	0.02 Hz–20 kHz
Lower limiting frequency (−3 dB)	< 0.02 Hz
Dynamic range	14–146 dB
Type of preamplifier	G.R.A.S. 26 CI
Frequency range (±2 dB)	1.2 Hz–100 kHz

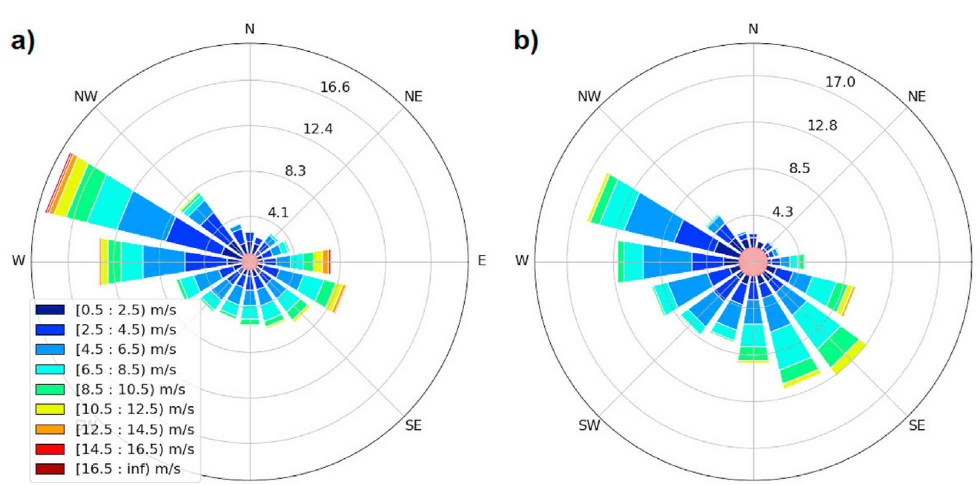

Fig. 6. Comparison of wind direction distribution a) in the year 2020 and b) in the time period corresponding to the measurement campaign from 2020 to 10–21 to 2020-12-16 (right) from data of the WINSENT test site.

Table 4
Overview of structural characteristics and surrounding conditions at the residential measurement locations. Information on the housing structure according to residents.

	Resident 1	Resident 2	Resident 3	Resident 4
Year of construction	1990	1990	1992	1920
House type	two-story single building	two-story single building	three-story terraced building located between two rows of buildings	three-story semidetached building
Facade Construction	brick wall; roof with roof tiles, rock wool, and air gap	solid construction	plastered bricks for exterior walls	solid construction gutted and re-clad with 8 cm insulation material
Window Setting	double glazing, mainly closed, opened briefly on occasion	triple glazing, mainly open	double glazing, closed	double glazing, closed
Visibility WT	WT 3 through both windows	WT 3 through southern windows	WT 3 through window	WT 3 through window
Distance to railway track	80 m	20 m	130 m	300 m
Figure	7a	7b	7c	7d

Table 5
Microphone positions at outside and inside measurement locations at the residential sides.

	B&K inside microphone	G.R.A.S. outside microphone
Resident 1	0.5 m above bed in bedroom 1st floor with sloping roof	at garage on same level in 2.2 m distance to southeastern facade
Resident 2	1.0 m above ground in bedroom 1st floor (bed without mattress)	in garden surrounded by bushes with 8 m distance to southeastern facade
Resident 3	0.7 m above bed in bedroom 1st floor	in garden with 6.25 m distance to northwestern building facade and 2.9 m to northeastern garage facade
Resident 4	1.30 m above ground in 2nd floor with sloping roof	in garden with 8 m distance to building facade and 4 m to garage facade

filtered and classified according to Ref. [57]. The given height resolution for the temperature at the WINSENT site in addition to the wind velocity and wind direction profiles of the lidar measurements and the meteorological masts can be assigned to the profile classes. The combination of these different profile classes with each other results in 1560 different varieties indicating a possible use of machine learning techniques. Furthermore, the variety of different stability and shear conditions have to be investigated.

3.1.3. Results

In this section, data for an exemplary day during the measurement campaign is presented. Fig. 5a shows that on this winter day (2020-12-05) the cloud height was mostly very low and broke up for a short time in the morning hours between 07:00 UTC, shortly after 09:00 UTC and again in the afternoon (red curve). The cloud cover indicates that it was an almost continuously cloudy day. There was some rain in the afternoon between 16:00 and 17:00 UTC, too.

Looking at the associated wind speed (dark blue, see Fig. 5b) at 100 m above ground - which corresponds to 764 m a.s.l. – measured at the WINSENT test site, it can be seen that there was sufficient wind to operate the WTs, especially during the night and afternoon hours. In particular, during the afternoon hours, the values increased to more than 8 m/s, which led to an operation of the WTs at partial load. It can be observed that the wind speed at an altitude of 513 m a.s.l. (light blue curve) was even higher around 15:00 UTC than the one at a layer 250 m higher (dark blue curve). The dropouts in the data of the light blue curve can be explained by the fact that the laser-optical lidar measurement system requires a certain backscatter and corresponding signal-to-noise ratio to determine the wind speed. If these conditions are not fulfilled, no wind speed can be determined.

The low wind speeds around 09:00 UTC and in the evening around 19:00 UTC are accompanied by a significant change in wind direction (Fig. 5c). Thus, the previously prevailing wind direction changes from west-north-west in the morning to east-south-east during the day by about 180°. In the evening hours, however, it changes again to north. The determined wind directions at 499 m a.s.l. and 750 m a.s.l. correlate quite well, whereas the almost recognizable constant deviation can be attributed to the influence of the orography of the respective locations.

Looking at the temperatures taken from one of the meteorological masts of the WINSENT test site (Fig. 5d), the temperature near the ground in the morning hours is lower than that recorded at 96 m above ground. Shortly after 09:00 UTC this changes for about 1 h. After the light rain in the afternoon, a significant increase in temperature at 96 m to about 3 °C is evident after 18:00 UTC, while the near-ground temperature is almost constant at about 0.5 °C. This could indicate a certain inversion layer. Looking at the lapse ratio (gray line), it also shows a corresponding increase shortly after 09:00 UTC and after 18:00 UTC. The stability parameter $\zeta = z/L$ shows almost continuously positive values during the day, which indicates an Obukhov length L greater than 0 and thus a stable stratification.

In the vicinity of the wind farm Tegelberg and the research test site WINSENT, both the orographic characteristic of the Alb escarpment and the joining of the valleys of the rivers Lauter and Fils create a complex situation. This leads to the fact that the wind direction and the air masses moving up or down the Alb escarpment have an influence on the emissions of the investigated WTs. The wind direction distribution and associated wind speeds from the northwestern meteorological mast are shown in Fig. 6 for the whole year of 2020 (Fig. 6a) and for a measurement period from 2020-10–22 to 2020-12-16 (Fig. 6b). It can be seen that the wind direction west-north-west is the most likely during the year as well as during the measurement period. In our measurement period there are also significant contributions from the south-eastern direction which do not occur as often in the full year period.

3.2. Acoustics

In addition to meteorological measurements, continuous

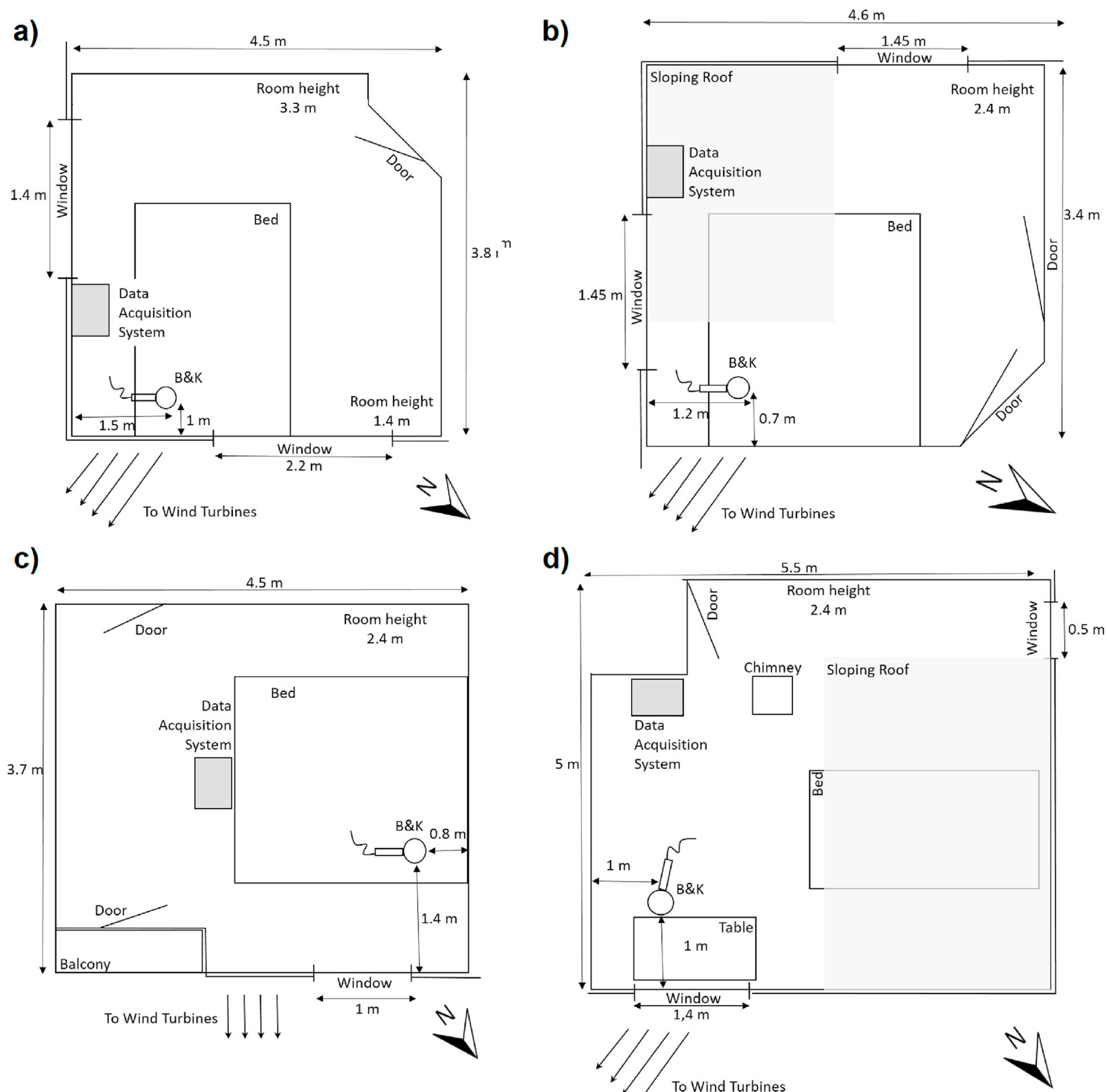

Fig. 7. Schematics showing the instrumentation set-up inside at a) resident 1, b) resident 2, c) resident 3, and d) resident 4. Exterior facades are marked with a double line. Additional information on microphone positions is listed in Table 5.

measurements of sound emissions (in the vicinity of the wind farm) and immissions (outside and inside of residential buildings) were conducted. The acoustic measurement campaign was conducted from October to December 2020. The measuring devices at the buildings were moved after two week periods on the same dates as the ground motion measurement equipment.

3.2.1. Instrumentation

At the wind farm site, the microphone was located approximately 140 m south of WT 1 (Fig. 3). Time series were recorded using a imc CRONOSflex data acquisitions system supporting a 4 channel sound card with 24 bit resolution, a maximum sampling rate of 20 kHz, and a lower cut-off frequency of 0.2 Hz. It was operated with imc Studio-PRO 5.2 software and data was stored on a separate computer. A G.R.A.S. 47AC 1/2 inch constant current power (CCP) free-field condenser microphone set for infrasound was positioned on a wooden groundplate with primary and secondary windshield. In addition to the acoustic data, meteorological data were recorded by a 10 m high meteorological mast at the wind farm location and a container was used as mobile control center for the data acquisition system. The distance between microphone and container was up to 14 m. Detailed information on the outside measurement equipment can be found in Ref. [31].

At the residential site a similar set up was used. Data was recorded with imc CRONOSflex data acquisitions system and stored with a network attached storage (NAS) using a NanoPi on one hard disk and mirrored to a second hard disk at regular intervals. At the outside location, the microphone and the set-up on a groundplate is the same as used at the wind farm. The data acquisition system was placed in the interior. At the inside location a Brüel&Kjaer 4964 1/2 inch free-field infrasound microphone with 26Cl G.R.A.S. preamplifier was installed. Detailed sensor information is specified in Table 3. The microphone was placed on a tripod. All recorded data was synchronized in time with a GPS signal.

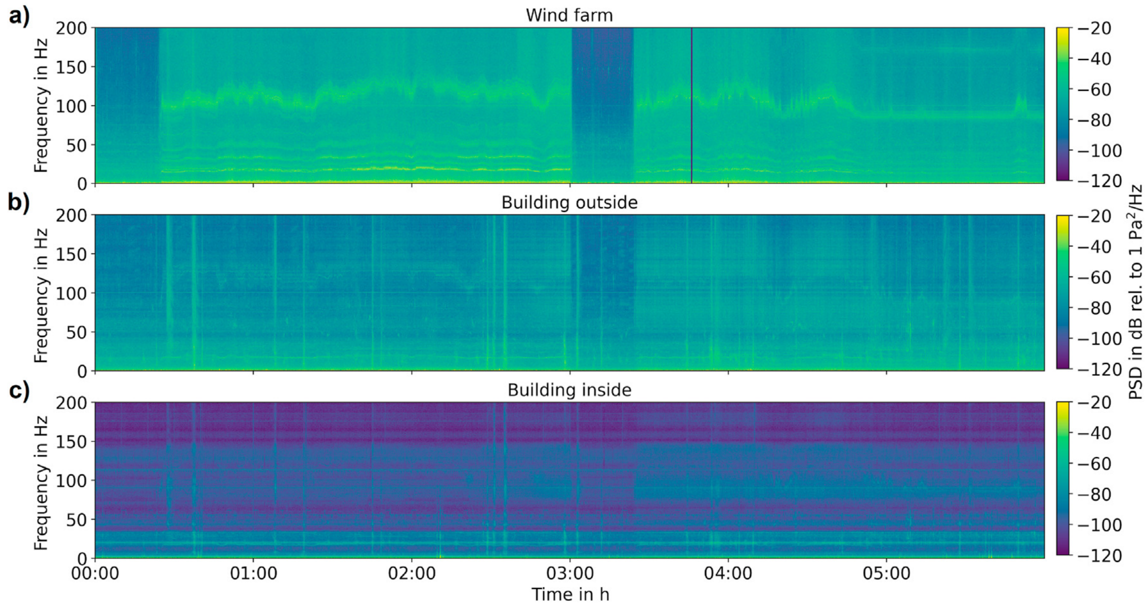

Fig. 8. Sound PSD for a 6 h time window at 2020-12-05 between 00:00 and 06:00 UTC and frequency range 1–200 Hz, a) at the northern WT 1, b) at the outside location at resident 3, and c) at the inside location of resident 3.

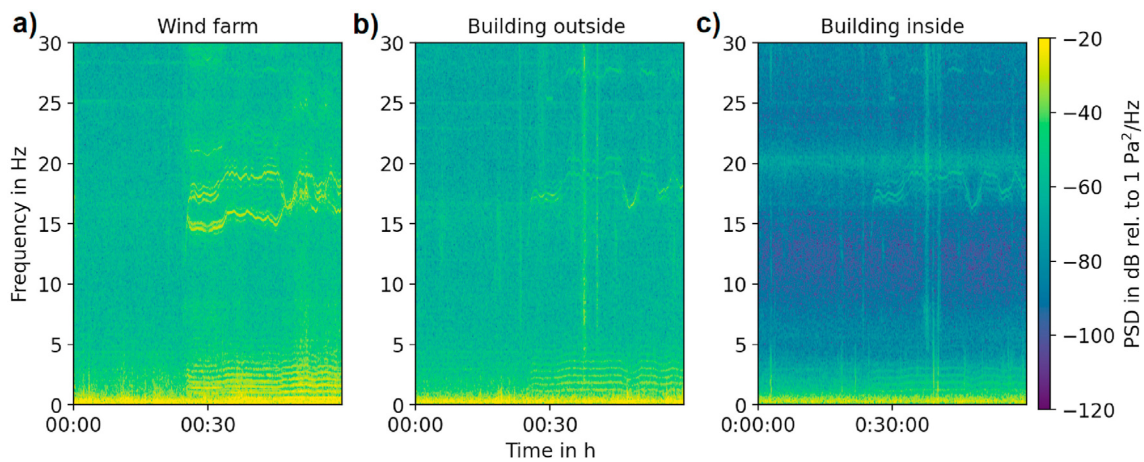

Fig. 9. Sound PSD for a 1 h time window at 2020-12-05 between 00:00 and 01:00 UTC and frequency range 1–30 Hz, a) at the northern WT 1, b) at the outside location at resident 3, c) and at the inside location of resident 3.

3.2.2. Description of residential sites

Acoustic immission measurements were carried out at four residential sites marked in Fig. 3. More detailed information regarding residential buildings, surroundings and measuring positions can be found in Table 4, Table 5 and Fig. 7. Three residents offered their bedroom for inside measurements and stayed in another room of the house during the measurement period. This procedure helped to achieve privacy protection and to avoid the influence of additional noise. The microphone was positioned above the bed, to imitate the sleeping position of the residents during nighttime (see Fig. 7). Furthermore, a railway line through Kuchen is used regularly by regional trains, intercity trains and freight trains. This must be taken into account when evaluating the acoustic data, especially for residential building 2 in the immediate vicinity of the tracks.

3.2.3. Data analysis

In order to obtain an overview of the acoustic data for all three locations (inside, outside and at the wind farm), spectrograms were calculated for the period of one day. The power spectral density (PSD) of the acoustic data is calculated for a time length of $T = 10$ s, a rectangular window length of $N_{win} = T \cdot f_s$ for $f_s = 500$ Hz, no averaging and 0% overlap, with the Python package matplotlib [58].

To analyze the WT sound at all three measurement locations the unweighted equivalent-continuous sound pressure level ($L_{p,eqT}$) was calculated for each 10-minute and 1-minute period. The values were calculated according to [59].

$$L_{p,eqT} = 10log_{10}\left(\frac{\frac{1}{T}\int_{t_1}^{t_2} p^2(t)\mathrm{d}t}{p_0^2}\right) \quad (1)$$

with p the instantaneous sound pressure, $p_0 = 20$ μPa the reference pressure and T the time period of 10 min or 1 min. Within this work, levels for the frequency range 1–200 Hz are considered. This

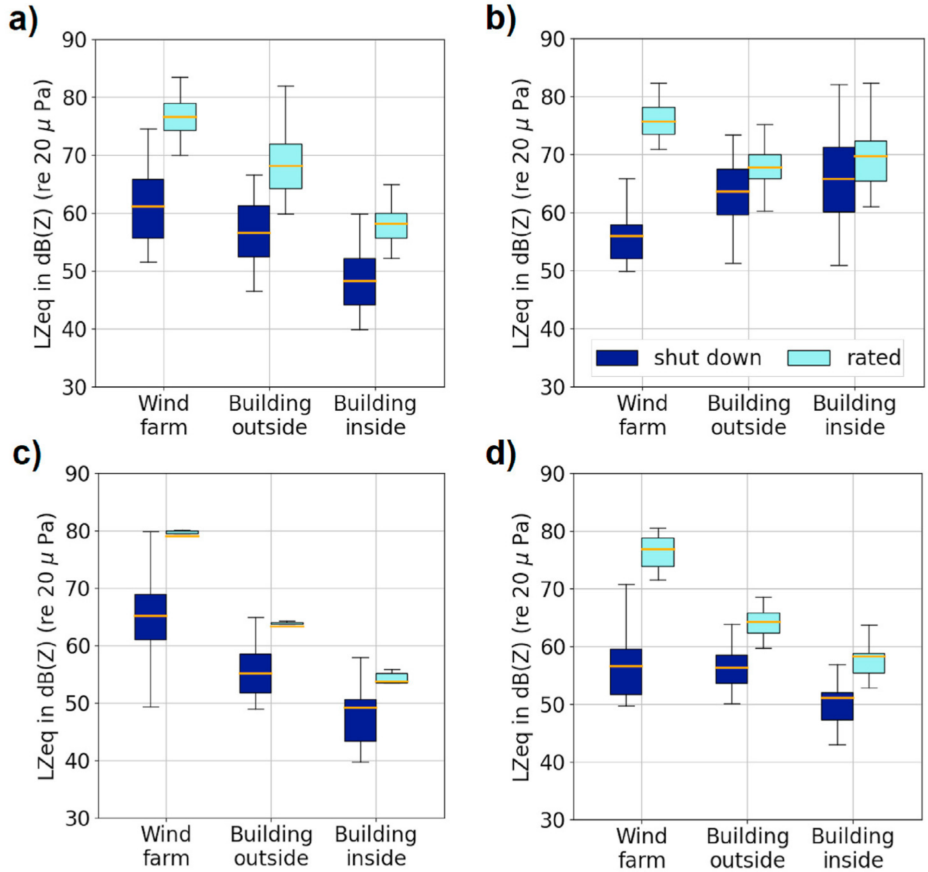

Fig. 10. Comparison of $L_{p,eq10min}$ (frequency range 1–200 Hz) for rated (11–12.6 rpm) and shut down (0–1 rpm) operation of WT 1, 2 and 3. Only nighttime data from 21:00–05:00 UTC and wind speeds of 0–4 m/s at 10 m height are considered. Orange lines indicate the mean value. Data from days during which the measuring devices were set up is excluded. a) resident 1 (60/34 data points for WT rated/shut down), b) resident 2 (74/79 data points), c) resident 3 (5/81 data points), and d) resident 4 (52/102 data points).

frequency range was chosen due to particular interest is the infra- and low-frequency sound in relation to annoyance. Furthermore, a comparison with the $L_{p,eq10min}$ values for the frequency range 1–1000 Hz showed only minor differences. Thus, the unweighted $L_{p,eq10min}$ is dominated by a low-frequency component.

No correction has been made for the reflection due to the mounting of both outside microphones on a ground plate. Data from days during which the measuring devices were set up are excluded in order to avoid any noise caused by installation and calibration. Data from rain periods was not excluded from the initial evaluations. For analysis of the unweighted $L_{p,eq10min}$, the measurement data at each resident was filtered based on a number of criteria. For a comparison between ambient and WT noise levels, data was selected for WTs operating in the full load range with rotational speeds between 11 rpm and 12.6 rpm and compared to shut down periods with rotational speeds between 0 rpm and 1 rpm. To clearly separate ambient noise and WT sound, data from night time during 21:00 and 05:00 UTC was included into the evaluation. To reduce wind induced noise at the microphone at the wind farm site, only data with maximum wind speed of 4 m/s at 10 m height was considered. In order to obtain sufficient data at all residential sites, the wind direction was not limited for this comparison. Box plots (Fig. 10) show the mean value of all data and the 25% and 75% quantiles in the box. The vertical lines indicate the maximum and minimum values occurring for the criteria.

3.2.4. Results

According to Chapter 3.2.3, PSD diagrams of the acoustic measurement data were calculated for a frequency range of 1–200 Hz and 1–30 Hz (Fig. 8 and 9). During this period, WT 1 and 3 rotated at speeds between 8 rpm and 12 rpm, the wind speed at hub height varied between 4 m/s and 9 m/s with western orientation of both WT nacelles. WT 2 was shut down during the period under consideration for maintenance reasons.

The upper diagram in Fig. 8a shows the acoustic signals for the measurement location close to WT 1. Here, the shut down times are clearly visible as the reduced PSD over the entire frequency range of about 1–200 Hz, indicated by the colour coding. Signal components that are only present during WT operation are of particular interest. Several tones with increased PSD can be detected in the frequency range between 10 Hz and 150 Hz, which can be assigned to WT operation. The frequencies of these tones vary over time and are proportional to the blade-passing frequency (BPF) and the strength of the variation increases with increasing frequency. The BPF and its multiples below 10 Hz are visible in Fig. 9a.

In Fig. 8b and c the PSD at the place of immission are presented. Despite a reduction of the PSD from outside to inside location considering the overall noise, shut down times of the wind farm can be identified. The tone fluctuating around 20 Hz is still visible at the residential sites, in contrast to the higher harmonics between 20 Hz and 100 Hz. The fluctuating signal component between

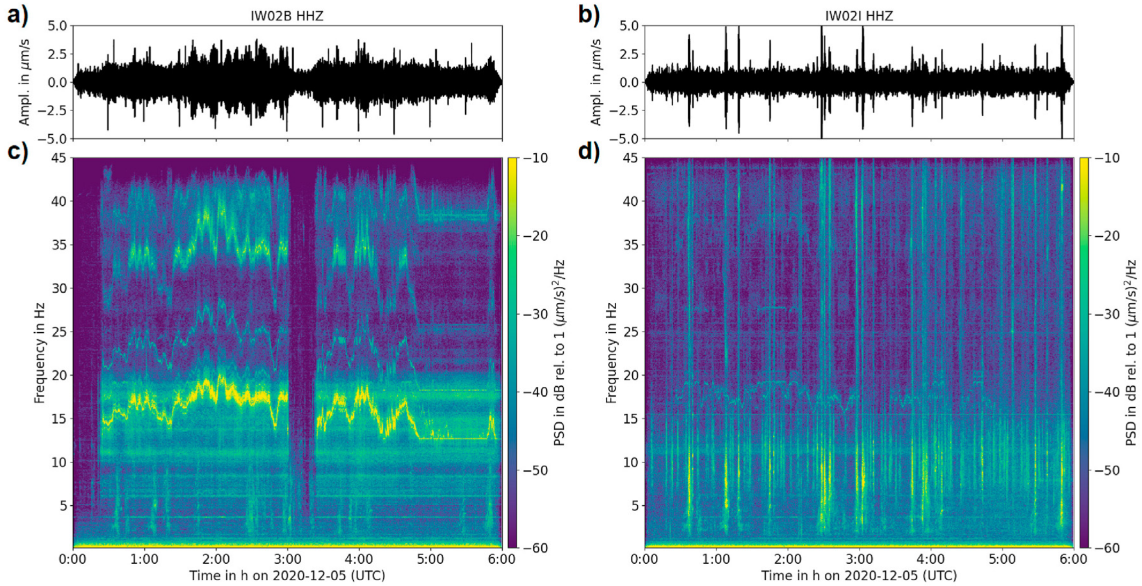

Fig. 11. Data example of the vertical ground motion velocity for a 6-h time window. a) and c) at the instrument located next to the acoustic measurement at WT 1, and b) and d) at the instrument at resident 3. a) and b): time series of the vertical ground motion velocity. c) and d): spectrogram with power-spectral densities for a frequency range of 0.1–45 Hz over the same time period as in the corresponding time series in the top panel.

100 Hz and 120 Hz is faintly visible at the outside location and rarely visible at the inside location, whereas the BPF and multiples can be detected in both locations very well (Fig. 9b and c). Other signal components can be assigned to the measurement location and are caused by other sound sources, the building structure or electrical noise at 50 Hz and 100 Hz. The vertical lines, both outside and inside, can be caused by short-term sound sources such as passing trains in 130 m distance, regularly occurring components at 60 Hz by household appliances and the continuous line at 20 Hz inside the building may be a structural resonance [60].

In order to illustrate the comparison of background noise and wind farm noise, the data was filtered due to the criteria described in Chapter 3.2.3. Fig. 10 shows filtered $L_{p,eq10min}$ for the measurement location at the wind farm, outside and inside the residential building divided into the four measurement periods (see Table 2). For the wind farm site similar $L_{p,eq10min}$ values are obtained for operating WTs during the whole measurement period with mean values between 75 dB and 80 dB. Background noise level is 15 dB and 20 dB below the WT sound pressure level. At the outside locations mean $L_{p,eq10min}$ varies between 64 dB and 68 dB for WT operating conditions with around 10 dB above the background noise level. Whereas at residential site 2 there is a difference of only 5 dB between wind farm and background noise. Similar tendencies in $L_{p,eq10min}$ are available for the inside measurements with 6 dB–10 dB level difference between background and WT noise. At residential sites 1, 3 and 4, the $L_{p,eq10min}$ decreases steadily from the wind farm to the inside measurement location. The situation at resident 2 is an exception, as an increase in levels can be seen from the outside to the inside location. On the one hand, the open window during the measurement period leads to higher levels, and on the other hand, the proximity of 20 m to the railway tracks with regular passage of passenger, express and freight trains. Freight trains in particular contribute to an increased low-frequency component in the frequency range between 10 and 160 Hz [61], which can lead to increased levels in the interior due to the excitation of the building structure. The strongly varying $L_{p,eq10min}$ of the ambient noise can also be caused by the wind, which has a greater influence through the open window than when the window is closed.

3.3. Ground motions

The three-dimensional ground motion velocity measurements were conducted in close proximity to the acoustic measurements at the northernmost WT of the Tegelberg wind farm (WT 1) and at four resident's sites in Kuchen. Additionally, one instrument was installed in the basement of the tower of WT 1 to register the source signal on the foundation of the turbine. Three additional measurement locations were set up in the forest between the wind farm and Kuchen to study the amplitude decay of the induced ground vibrations. All instruments were set up in October and November 2020. The ground motion instrumentation at the residential sites was moved after two week periods on the same dates as the acoustic measurement equipment. Recorders in the field and in the WT tower were kept in place until February 2021.

3.3.1. Instrumentation

Trillium Compact Posthole (TC-PH) sensors with 20 s eigen period and Nanometrics Centaur digitizers were used for the measurements at the resident's sites. The sensitivity of the instruments is 750 Vs/m, the lowest recordable signal in the operating range is in the order of 1 nm/s. For the field recordings Trillium Compact and Lennartz LE-3Dlite (1 s eigen period, 400 Vs/m sensitivity) sensors were installed. These measurement points were operated with a DATA-CUBE[3] recorder and powered by a battery. Each recorder was equipped with a GPS antenna for time synchronisation. The sampling frequency was set to 100 Hz, resulting in a frequency range of 0.05–50 Hz for the TC-PH sensors and 1–50 Hz for the LE-3Dlite sensors. The recording within the WT 1 tower was done with a Streckeisen STS-2 broadband sensor with an eigen period of 120 s (leading to a frequency range of 0.008 Hz–50 Hz) and data were stored with an EarthData Portable Field Recorder (EDL-PR6-24). All sensors have three components: vertical, North-South and East-West. Orientation of the sensors

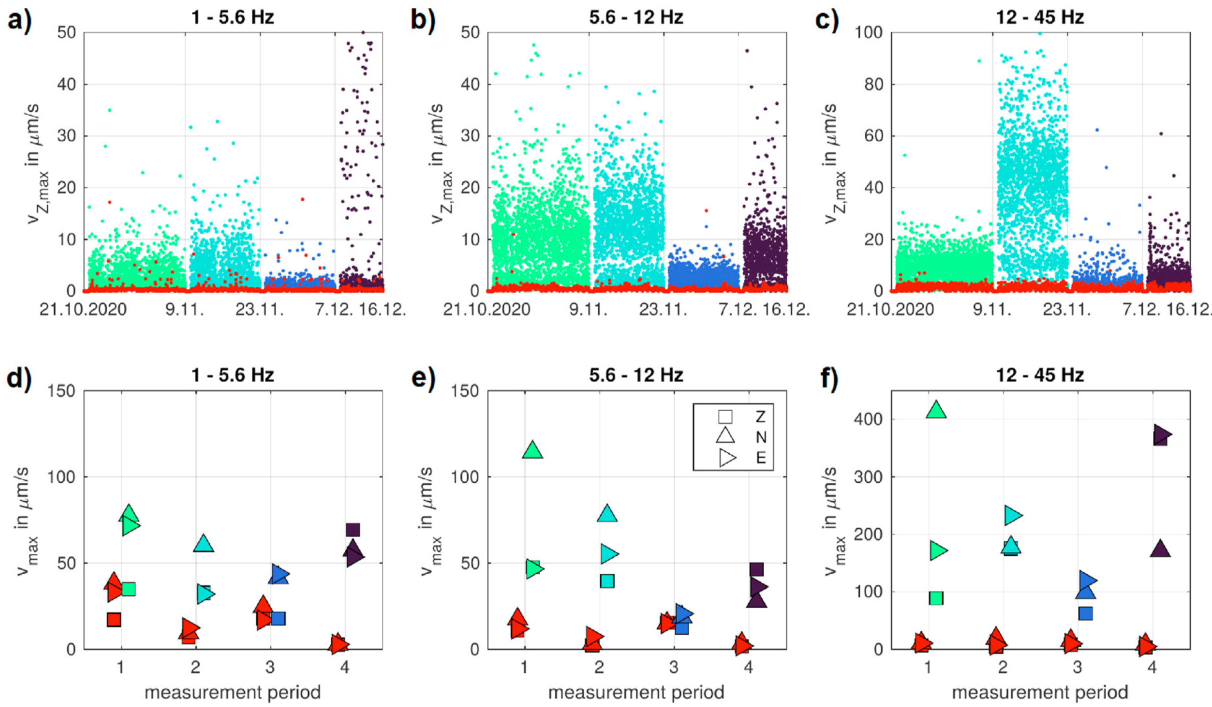

Fig. 12. Comparison of maximum ground motion amplitudes at the outside resident measurements (green and blue colors) and near WT 1 (red). a)-c): 10-min maximum amplitudes of the vertical ground motion velocity for three different frequency ranges (1–5.6 Hz, 5.6–12 Hz, 12–45 Hz). Days when the resident instrument location was changed are excluded. d)-f): Overall maximum amplitude during the measurement period at the residential sites and the recording near WT 1. Different symbols indicate maximum values for the three different components (vertical, N-S, E-W).

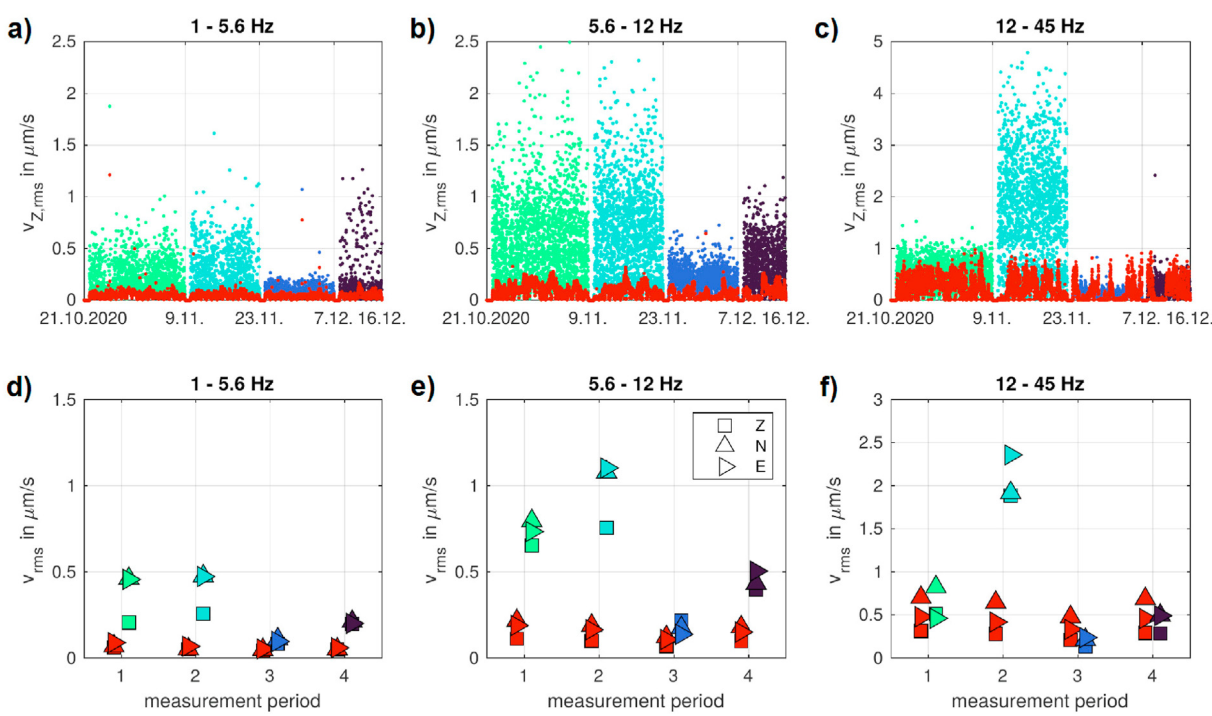

Fig. 13. Comparison of rms amplitudes at the outside resident measurements (green and blue colors) and near WT 1 (red). a)-c): 10-min rms amplitudes of the vertical ground motion velocity for three different frequency ranges (1–5.6 Hz, 5.6–12 Hz, 12–45 Hz). Days when the resident instrument location was changed are excluded. d)-f): Overall rms amplitude during the measurement period at each of the residential sites and the recording near WT 1. Different symbols indicate rms values for the three different ground motion velocity components (vertical, N-S, E-W).

Table 6
Correlation coefficients for 10-min ground motion amplitude data from the instrument near WT 1 with the rotation rate of WT 1 in rpm. For the recordings from the residents a correlation coefficient of 0.13 and less was calculated for each measurement period, indicating negligible correlation of ground motion amplitudes with rpm.

	1–5.6 Hz	5.6–12 Hz	12–45 Hz
corr(v_{max},rpm_{WT1})	0.05–0.37	0.36–0.78	0.48–0.79
corr(v_{rms},rpm_{WT1})	0.3–0.7	0.75–0.84	0.54–0.82

towards north was accomplished with the help of a gyrocompass.

At each residential site the sensor was placed near an outer wall of the main building, and at resident 4 it was located near a shed close to the main building. In each case there was a paved underground and a close-by wall for shelter against wind and precipitation. The sensors were insulated with bubble wrap and a styrofoam box against temperature fluctuations, while the recorder, including the digitizer, and further equipment were stored in a lockable box nearby. At the third resident an additional instrument with the same setup was installed in a basement room to compare inside and outside signals. All field instruments were buried in approximately 30 cm depth and covered with soil for insulation and cover.

3.3.2. Data analysis

The true ground motion velocity is calculated from the raw data by the removal of the instrument response. Then a 2-pole bandpass filter with corner frequencies of 0.1 Hz and 45 Hz is applied. As examples, two 6 h-long time series (seismograms) of the vertical ground motion velocity from the instrument near WT 1 and the instrument at resident 3 are presented in Fig. 11a and b. Spectral analysis by the method of [62] is applied, using 60 s time windows with an overlap of 20 s to calculate PSDs. These are displayed in Fig. 11c and d and show the measured signals in the frequency domain as spectrograms. In the recordings near WT 1 horizontal lines of increased PSD are visible that represent constantly excited frequencies by WT operation corresponding to the eigen modes of the WTs. At frequencies above 12 Hz we observe signals which change frequency with time and are proportional to the BPF. They can be observed at the same frequencies in the sound pressure data, which indicates a common source, which is most likely the WT generator. Between 12 Hz and 45 Hz three distinct tones can be observed. These signals are faintly visible at the instrument at resident 3 as well. Here the spectrogram (Fig. 11d) is dominated by vertical lines, indicating transient signals. They are caused by trains passing through the town of Kuchen at intervals of several minutes. The stronger signals, corresponding to train passages, can even be observed below 10 Hz at the instrument near WT 1 which is located approximately 1 km off the train tracks.

During the time window shown in Fig. 11 WT 1 and WT 3 were in operation with rotation rates ranging between 8 rpm and 12 rpm. In the recordings near WT 1 the two shut down periods at 00:00 and 03:00 UTC are well visible. The ground motion velocity near WT 1 does not surpass 5 μm/s, while at resident 3 only during some of the train passages amplitudes of more than 5 μm/s are reached. Overall the signal level in both recordings is of comparable amplitude. However, note that the ground motion due to the WTs cannot be clearly identified at resident 3 because it vanishes in the background noise.

To evaluate the ground motion amplitudes of the measured signals during the four measurement periods full-day, 10-min maximum and rms amplitude values are determined. Recordings for each of the three components are used and split into three frequency intervals of 1–5.6 Hz, 5.6–12 Hz and 12–45 Hz. Thereby, signals resulting from WT eigen modes (< 12 Hz) and signals proportional to the BPF (> 12 Hz) are separated. Furthermore,

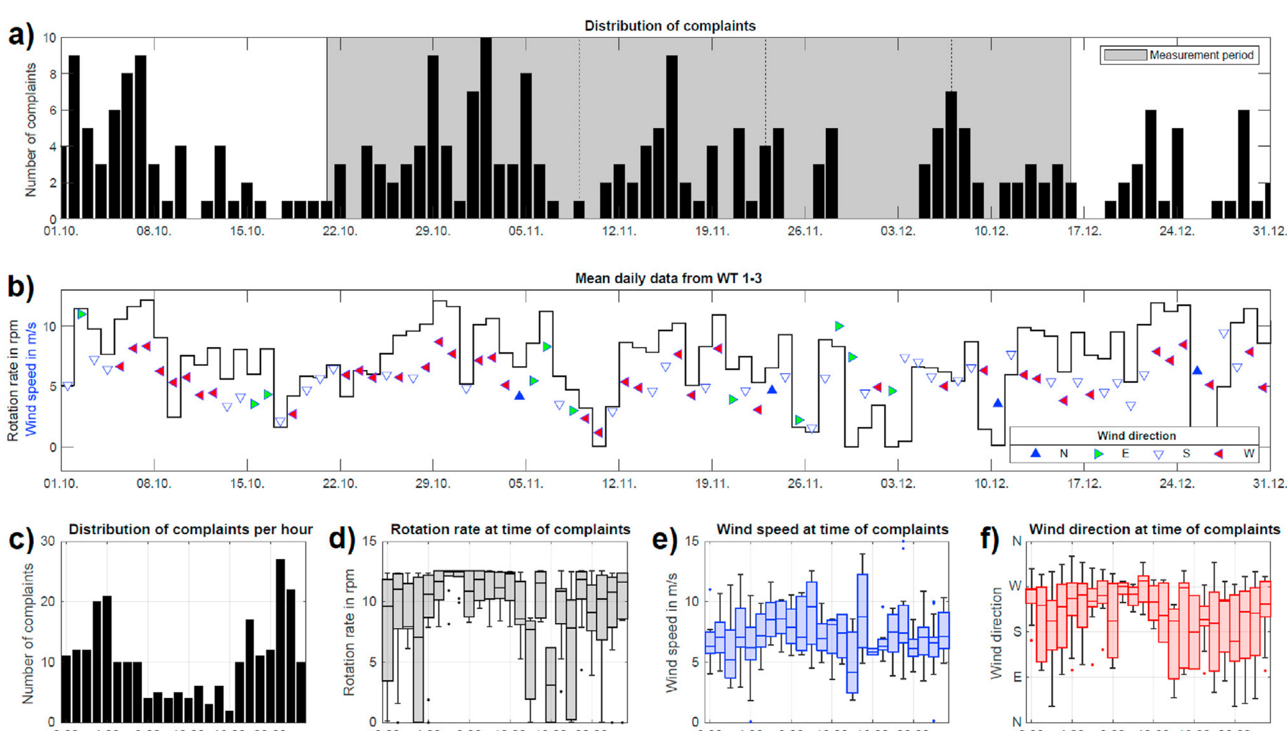

Fig. 14. a) Overview of the number of complaints registered through the app for October to December 2020 with the period of acoustic and ground motion measurements indicated by the gray shaded area and b) mean daily operating and meteorological data of WT 1–3 for the same period. c) Distribution of the complaints by hour and d)-f) the corresponding WT data at the time of complaints.

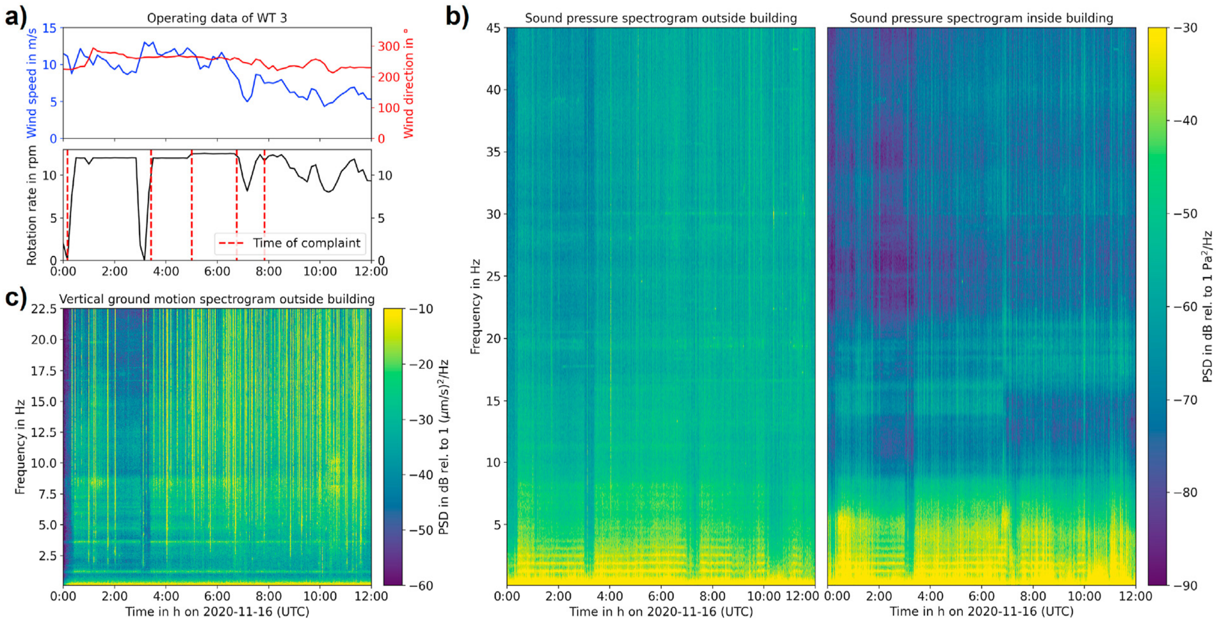

Fig. 15. Case example for 2020-11-16 with complaints registered through the app in relation to a) the operating data of WT 3, b) the sound pressure and c) ground motion measurement data.

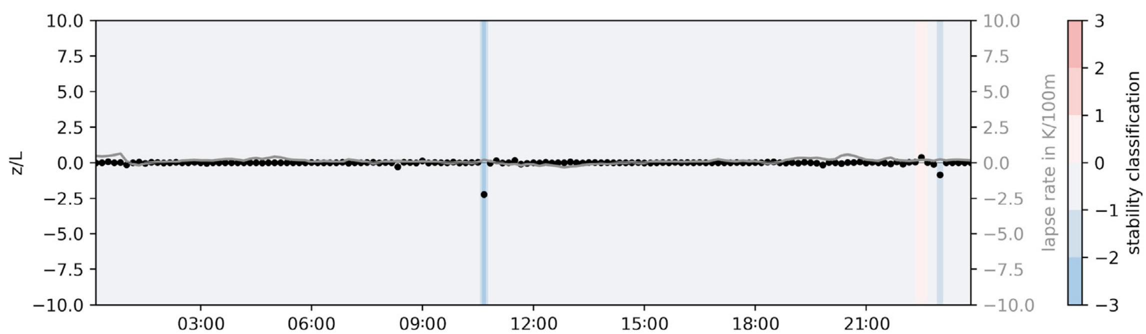

Fig. 16. Data for 2020-11-16 showing the atmospheric stability classification at the WINSENT test site.

following DIN 4150-2 5.6 Hz is taken as a lower limit for signals relevant to human perception. Days when the instruments were installed at the residents are excluded, to prevent analysing signals resulting from installation and instrument handling possibly present in the data.

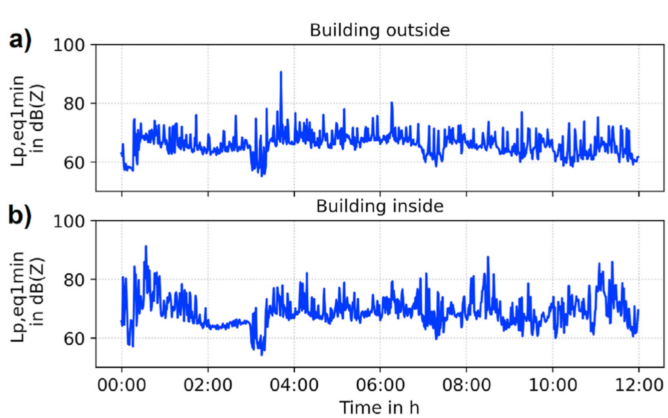

Fig. 17. $L_{p,eq1min}$ in dB(Z) (re 20 μPa) for the frequency range 1–45 Hz. a) outside building and b) inside building on 2020-11-16 between 00:00 and 12:00 UTC.

3.3.3. Results

Continuous recordings from the four measurement periods at the individual residents last 18, 13, 13, and 8 days (without installation days), respectively. During each period the percentage of time when WT 1 and WT 3 were in operation was 86%, 82%, 56%, and 69%, respectively.

Fig. 12a–c shows the distribution of maximum amplitudes of the 10-min segments during the measurement time from October to mid-December 2020. An increase in maximum amplitudes with higher frequencies can be observed. While the amplitudes near WT 1 are rather uniform large differences in maximum amplitudes for the individual residents can be recognized. Differences are especially significant in the frequency range of 12–45 Hz. The trend of maximum amplitudes can be related to the distance of the measurement sites to the train tracks which is 80 m (resident 1), 20 m (resident 2), 300 m (resident 3), and 130 m (resident 4). The overall maximum amplitudes (Fig. 12d–f) indicate that near WT 1 the ground motion velocity lies below 50 μm/s during all 10-min time windows, while at the residential sites maximum amplitudes of

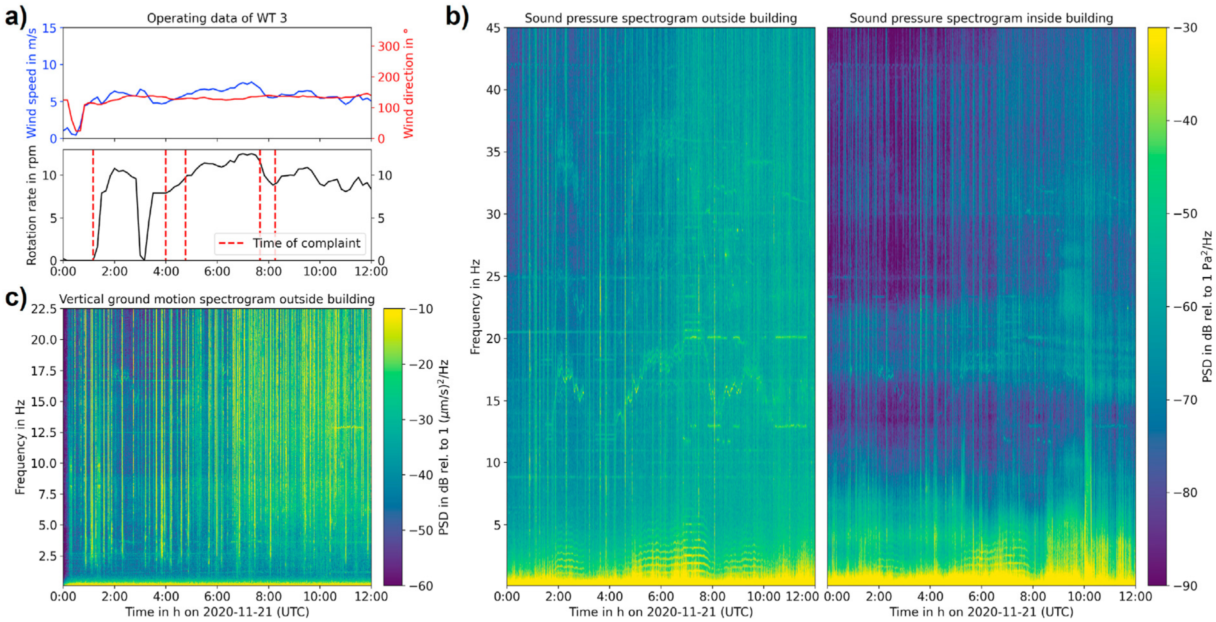

Fig. 18. Case example for 2020-11-21 with complaints registered through the app in relation to a) the operating data of WT 3, b) the sound pressure and c) ground motion measurement data.

Table 7
Overview of residents' noise reports during 2020–11-16, 00:00–12:00 UTC. Level of annoyance (LoA) is measured on a scale of 0 (not at all annoyed) to 4 (very annoyed).

Time (UTC)	LoA (0–4)	Description of sound	Disturbed during …	User's comment
00:10	4	swooshing, disquiet, felt the sound	sleep	bad sleep afterwards
03:25	3	rotor blade sounds, hit of a tennis racket at higher wind speeds	sleep	
03:26	4	swooshing	sleep	
05:00	3	rotor blade sounds, droning of an aircraft	sleep	windows were closed
07:49	2	wavelike aircraft sounds		sounds are permanently present

more than 400 μm/s are reached. At the residential sites 99% of the 10-min maximum amplitudes are below 110 μm/s for 12–45 Hz and below 47 μm/s for 1–12 Hz. In general, 99% of the maximum amplitudes are below 8 μm/s for 12–45 Hz (below 2.5 μm/s for 1–12 Hz) at the station near WT 1.

The rms amplitudes (Fig. 13a–c) show a pattern similar to the maximum amplitudes at the residential sites. Amplitudes near WT 1 are increased in relation to the amplitudes at the residential sites during the respective time period and a clearer variation over time is found. Overall the amplitudes of the horizontal components are larger than those of the vertical component (Fig. 13d–f). Near WT 1 especially the N-S component at 12–45 Hz has almost double the rms amplitude of the E-W component. This amplitude relation may indicate that the main direction of vibration is in line with the propagation direction of the ground motion waves emitted from the WT which is located approximately to the north of the recording sites (Fig. 3).

Near WT 1 the ratio of maximum to rms amplitudes is 5–15 in the frequency range of 1–5.6 Hz and ~5 in the frequency range of 5.6–45 Hz. At the residential sites the ratio is 10–20 for 1–12 Hz (30–50 in a frequency range of 1–5.6 Hz at resident 4), and 15–30 for 12–45 Hz. This implies that at the residential sites transient signals are responsible for the much higher maximum amplitudes while near WT 1 signal variations occur over a longer time frame.

Finally, the ground motion at the residential sites is compared with the operation of WT 3, which is the closest to the measurements. For this purpose correlation coefficients are determined to evaluate which data can be related best to the WT operation. At the residential sites correlation coefficients lie below 0.13 for all amplitude data when correlating them with the rotation rate of WT 3, which is the closest WT to the town of Kuchen. Near WT 1 (Table 6) correlation coefficients of up to 0.84 can be found indicating moderate to high correlation for rms values and frequencies above 5.6 Hz and a weaker correlation for maximum amplitudes. Differences arise for the four measurement periods due to the varying time and mode of WT operation.

4. Interdisciplinary analysis

To illustrate how an interdisciplinary approach provides a better understanding of noise annoyance than an approach which is less multi-faceted, in the following chapter it is shown how the different kinds of data can be merged and how they complement each other.

4.1. Comparison of annoyance times with WT data

In order to obtain an overview of the app data and to determine initial patterns leading to complaints, the data are first evaluated together with the WT operating data (see Fig. 14). The wind farm operator provided 10-min averaged operating data for all three WTs for the period from 2020-10-01 to 2020-12-31 including rotation rate, nacelle position (which can also be considered as wind direction), and wind speed.

Fig. 14a shows the number of complaints per day, registered through the app from October to December 2020. The time period

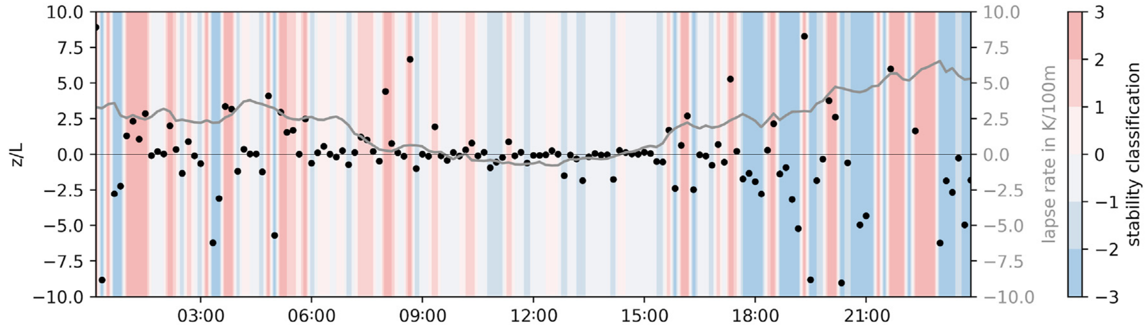

Fig. 19. Data for 2020-11-21 showing the atmospheric stability classification at the WINSENT test site.

Table 8
Overview of residents' noise reports during 2020–11-21, 00:00–12:00 UTC. Level of annoyance (LoA) is measured on a scale of 0 ″not at all annoyed″ to 4 ″very annoyed″.

Time (UTC)	LoA (0 −4)	Description of sound	Disturbed during …	User's comment
01:10	1	nothing noteworthy to hear	sleep	
04:00	4	rotor blade sounds, rhythmical lasting droning	sleep	windows and shutters closed
04:46	3	gearing sounds with east wind	sleep	sound remained in mind
07:40	3	bubbling, Bunsen burner, fidgety "movement"	sleep	rotors perpendicular to house, sound not loud but bubbling is particularly annoying
08:15	4	obtrusive gearing sounds	leisure activities	temperatures around freezing

marked in gray indicates the period with parallel acoustic and ground motion measurements and the dashed lines mark the days on which the measuring devices were set up and/or disassembled on the residential sites. Up to ten complaints were reported per day, while most of the complaints (around 85%) were registered during night time between 17:00 and 08:00 UTC (Fig. 14c). For the same time period rotation rate, wind speed, and wind direction of all three WTs are averaged over each full day (Fig. 14b) to be comparable with the app data. At the wind farm location the mean daily wind direction is dominantly south or west during around 79% of the time.

Fig. 14d-f display the distribution of WT data over the course of an entire day coincident with the time of complaints. During the day most of the complaints were registered during rotation rates above 8 rpm. At rotation rates below 8 rpm, approximately 2.6 (SD = 1.5) complaints were registered, whereas up to 4 (SD = 2.7) complaints were received at rotation rates above 8 rpm. It is noticeable, that certain complaint times occur during larger ranges of rotation rates which are 00:00, 03:00, 14:00, 16:00 and 18:00 UTC. This fits in part with the periods with the most complaints around 03:00 and 18:00 UTC. This could indicate that increased variability of rotation rates tends to lead to higher annoyance. Complaints around 21:00 UTC can be related to higher rotation rates between 8 rpm and 12.5 rpm. With regard to the dependence of the complaints on the wind direction, Fig. 14f shows that mainly wind from west and south was blowing during the considered time periods, but no clear relation to the times of complaints can be found. The same applies to hub height wind speeds. During nighttime, there is a lower variation of wind speeds with mean values around 6 m/s to 7 m/s than during daytime with mean values between 7 m/s and 9 m/s. It follows that the rotation rate of the WTs is particularly suitable for comparison with the complaint periods.

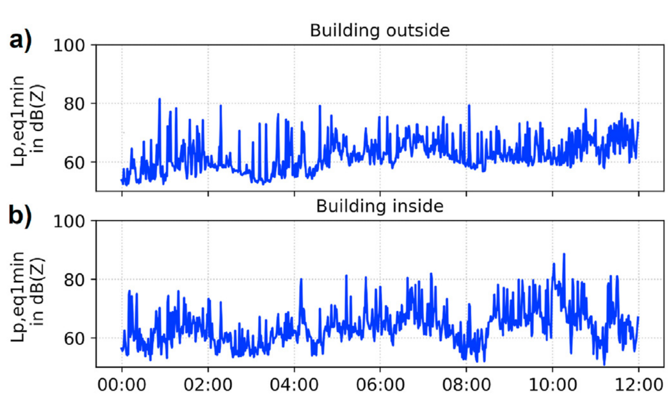

Fig. 20. $L_{p,eq1min}$ in dB(Z) (re 20 μ Pa) for the frequency range 1–45 Hz. a) outside building and b) inside building on 2020-11-21 between 00:00 and 12:00 UTC.

4.2. Case examples

To merge all data from Chapters 3.2.4, 3.3.3 and 4.1, two time periods with different operating conditions are chosen. For a comparison of meteorological, acoustic and ground motion measurements with WT and app data, time series from 12 h measurements are plotted as spectrograms and shown in Fig. 15 and 18 for two different days in November. Both periods are chosen due to a high number of complaints.

Fig. 15 provides insight into the relationship of data from WT 3, complaints from residents, acoustic and ground motion measurements at residential site 2 on 2020-11-16. During this period, WT 3 operated in full load range and rotated at maximum speed (with noise reduced operation mode up to 05:00 UTC), while WT 1 and 2 were rotating with maximum speed. After 07:00 UTC all WTs operated with rotation rates between 9 rpm and 12.5 rpm. The wind speed at hub height varied between 5 m/s and 12 m/s with the wind coming from southwestern and western direction (see Fig. 15a). This specific day was selected as mixed air layers over the course of the day lead to a constantly neutral atmosphere as is shown in Fig. 16 reducing variation of variables. Except for a 2 h period in the night between 01:00 and 03:00 UTC with light rain, no precipitation was measured.

Five noise reports by five different users were registered through the app. Table 7 gives an overview of the residents' noise reports in the app concerning time and noise character. The first two complaints with the highest levels of annoyance were documented during or after a shut down. At 03:25 UTC (04:25 local time) there are two overlapping reports by users. The third complaint was documented during the transition from noise-reduced operation to normal operation mode. The other two complaints are during full load operation of the WT. Although the descriptions of each user are different, they could be broadly related to aerodynamic noise generated at the rotor blade of a WT.

In Fig. 15b the PSD diagrams for the acoustic measurement data (0–45 Hz) from outside and inside the residential building are shown. The measurement locations are specified in Table 4 and Fig. 7. The ground motion instrument was placed between the railway tracks and the building, in close proximity to the facade. Fig. 15c shows the measured ground motion for a frequency range of 0–22.5 Hz.

In both, the ground vibration and airborne sound measurements, WT shut down times are visible at 00:00 and 03:00 UTC. Signal components that are only present during WT operation can be assigned to WT operation. In the acoustic data sample (Fig. 15b) multiples of the BPF below 10 Hz are visible outside and inside the residential building, in contrast to the ground motion measurements (Fig. 15c). In contrast to the outside data, the power density decreases between 8 Hz and 12 Hz at approximately 07:00 UTC in the inside data as shown in Fig. 15b. An increased PSD around 8 Hz, which is not present during shut down times, can be identified in the acoustic and ground motion data. In all spectrograms, vertical lines can be assigned to train signals, due to the proximity (20 m) of the measurement positions to the rails with a high frequency of passing trains.

Additionally, Fig. 17 shows the unweighted $L_{p,eq1min}$ averaged over 1-min for the same frequency range of 1–45 Hz considered in Fig. 15b. In the timeseries of the acoustic data measured at the two measurement positions at residential site 2, the shut down times of the WTs at 00:00 and at 03:00 UTC are clearly visible. Since the window was open during the measurement period at resident 2, there is almost no difference in the sound pressure level between outside and inside microphone position.

Fig. 18 shows the combined data for 2020-11-21 (measurements at residential site 2) from 00:00 to 12:00 UTC. During this period, the rotational speed of WT 3 varied between 0 rpm and 12.5 rpm. WT 1 and 2 were rotating with similar rotation rates as WT 3, while the wind speed at hub height varied between 0.5 m/s and 8 m/s with the wind blowing from southeastern direction (see Fig. 18a). During the time period fluctuations of the atmospheric conditions were observed, with low wind speeds and increased mixing of the air layers leading to unstable atmospheric conditions (see Fig. 19). No precipitation was measured over the course of the day.

In the considered time there were again five noise reports registered through the app, this time by three different users (Table 8). The first complaint is documented during a shut down of all three WTs. This is exactly the condition that the resident noted in the app, highlighting the perception of different conditions by the residents also during sleeping hours. For the following complaints, sound descriptions are related to aerodynamic, but also mechanical sounds of the WT, like gearbox noise (Table 8). In the 12 h period, the WTs rotated with approximately 9 rpm when complaints were related to gearbox noise, whereas the other complaints are related to rotational speeds above that rate apart from the one complaint during shut down.

Fig. 18b and c show the spectrograms for the acoustic and ground motion measurement data at the same measurement locations as on 2020-11-16. Here, the shut down times are not as clearly distinguishable from the period with rotating WT as in Fig. 15. However, a fluctuating signal component between 10 Hz and 20 Hz is visible in all spectrograms, which is related to the rotational speed. In addition, multiples of the BPF, which vary over time in relation to the rotational speed of the WTs, can be identified in the acoustic data (Fig. 9b).

Fig. 20 shows the unweighted $L_{p,eq1min}$ averaged over 1-min for the same time period. As found in Fig. 18b, there are no significant level differences between the period with rotation and shutdown of the WT. Again the signal was measured at residential site 2 with an open window, which results in similar outside and inside $L_{p,eq1min}$.

5. Discussion

In previous studies [47–49] mostly flat terrain locations were under investigation considering WT noise effects. In this study the focus is on a town located in a valley lying beneath the wind farm that is elevated 300 m compared to the town (Fig. 3). The topography could promote currents that influence sound propagation and could therefore provide new insight into noise occurrence and perception. Furthermore, in the town of Kuchen a federal road as well as a major railway line exist, providing additional noise sources, which are common in many places.

With regard to noise annoyance the wind farm Tegelberg is a special case, as 33.1% of the residents are found to be strongly annoyed. Comparable studies with similar recruitment methodologies and samples find 1.1%–9.9% of strongly annoyed residents [6,7,63]. Therefore, this location is well suited for a detailed study. Due to the high number of annoyed residents it is likely that sufficient people are willing to participate in measurements. The high interest in results from the local community also enables a long term surveillance with repeated measurements. Furthermore, wind farm operators are interested in resolving conflicts such that detailed operating data of the WTs are provided.

Residents were offered the use of an app through which complaints could be issued from 2020-08-08 to 2021-02-03. A total of 17 users participated in this study by issuing complaints in a more or less regular fashion. This offered the opportunity to get spontaneous annoyance reactions by those most affected, which are crucial to evaluate a realistic everyday setting. In this approach, though, mostly moments are captured when the app users experience annoyance connected to the WTs. Comparing situations with annoyance to situations without makes for a clearer distinction of the characteristics of these situations. Therefore, for future studies, it could be beneficial to encourage app usage also in cases when there was no annoyance. Regular use of the app by residents and documentation of whether or not noise is present could improve the attribution to WT operation modes.

With regard to the noise reports, the classification of the sounds into categories (Table 7 and 8) is helpful in the evaluation. Residents' comments on the annoyance periods show that in addition to the type of noise, residents also take into account environmental parameters such as the orientation of the WT or temperatures and weather conditions. A drawback of this study is that not all residents who participated in the measurements used the app. Noise reports of other app users are available, but their locations differ from the measurement sites and therefore they may perceive the sounds in a different way. Furthermore, the precision of the reports can sometimes be uncertain. In some cases, the time when the app was used differed significantly from the time stated of when the annoyance was observed. The advantage of using an app (in contrast to a handwritten diary, for example) is that it records the time of usage, so that these cases can be identified.

In order to determine the reasons for annoyance caused by WTs, a combination of ground motion, acoustic and meteorological measurements together with the noise report app (Fig. 15 and 18) provides a good foundation to investigate the origin of annoyance. A prerequisite for the comparability of the different data sets is time-synchronized measurement data, including noise reports by residents via the issued app. Synchronisation of the different measurements was achieved via GPS. In addition, the measurement and the app data could be assigned to the WT operation, as operating data of all three WTs were provided by the wind farm operator. shut down intervals of the wind farm (Fig. 8 and 11) were regularly implemented during night time to be able to identify background noise. Measurements over a period of two months enabled the detection of different weather and WT operating conditions and thus provides the opportunity to assign increased annoyance to these conditions.

Measurements were conducted at the northernmost WT of wind farm Tegelberg (WT 1, Fig. 3), because it is on an open field offering more open space for instrument installation compared to the other WTs which are located within the forest. Acoustic and ground motion measurements in the direct vicinity allows for the identification of typical WT related signals. These signals can partly also be identified in measurements at the residential sites but are, as expected, of much lower amplitude (Fig. 9). Residents involved in the measurement campaign mostly observe WT 3, which is located closest to the town of Kuchen. To improve the credibility of the results of the emission measurements in the next campaign instruments should be installed near WT 3, although no major differences in the observation of WT related signals are to be expected.

Joint measurements of acoustics and ground motions show that multiples of the BPF below 10 Hz are mainly detectable in the acoustic and not the ground motion data (Fig. 8 and 11). In the ground motion data frequencies below 12 Hz are dominated by the eigen modes of the WT tower. Signals with frequencies proportional to the BPF between 12 Hz and 45 Hz can be measured with high amplitudes in both the ground motion and acoustic data and can be assigned to the turbine operation. By cross-referencing the data of both methods together with the train timetable, signals from passing trains can be identified which contribute significantly to the overall amplitude level at the residential sites, especially in the ground motion data (Fig. 11).

The evaluation of the app data together with operational parameters of the three WTs (Fig. 15 and 18) demonstrates that increased WT operation is related to a higher number of complaints issued through the app. Users are most sensitive to WT noise during night time (Fig. 14). At certain time intervals a large spread of rotation rates can be observed, which could be related to complaints due to a change of rotation rate in the concerned time interval. One possible explanation is that the associated changes in amplitude and frequency might attract residents' attention. Sound changes are not exclusive to WT noise and also apply to another relevant noise source in the vicinity, e.g., train traffic. But in contrast to train traffic, changes in WT sound do not follow timetables and are less predictable. As the trains have been driving for decades on these tracks, comments during the interviews indicate habituation to their sounds. Furthermore, the description of the perceived noise (Table 7 and 8) indicates that app users can identify sound related to the WT operation well. A link of operation data to observations in the measured acoustic and ground motion data can be established, but in the future also meteorological data should be integrated in the evaluation.

6. Conclusion & outlook

In this study data from an interdisciplinary research group is combined in order to assess the annoyance of residents affected by WT emissions. Measurements of acoustic, ground motion and meteorological data were conducted in the vicinity of a wind farm in parallel with the registration of annoyance reports via an app. The measurement campaign was carried out for two months in November and December 2020 to capture high wind speeds and, therefore, most likely periods of high annoyance.

WT related signals can be recorded by acoustic and ground motion measurements in the vicinity of the WTs and, to a lesser extent, at the four residential sites. Furthermore, background noise like signals from passing trains can be identified, influencing especially the ground motion data.

Comparing app data to WT operation data indicates higher complaint rates in the early morning as well as evening and night times. Furthermore, changes in rotation rate seem to be the cause of annoyance as well as high rotation rates. As the wind direction is dominantly south or west, most complaints are related to these wind directions while at evening and night times also complaints during south-eastern wind directions occur.

Based on findings from the first measurement campaign, mitigation measures can be implemented by the wind farm operator. This provides the opportunity to evaluate these measures by a follow-up measurement campaign with a similar comprehensive design. During the follow-up campaign, residents should be encouraged to use the app more regularly, even at times of low annoyance. This procedure would improve the assignment of acoustic, ground motion and environmental factors to strong annoyance, planning of adapted counter measures and possibly more acceptance of WTs by local residents.

CRediT authorship contribution statement

Laura Gaßner: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Esther Blumendeller:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft. **Florian J.Y. Müller:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Maayen Wigger:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization. **Andreas Rettenmeier:** Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – original draft. **Po Wen Cheng:** Funding acquisition, Project administration, Resources, Supervision. **Gundula Hübner:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision. **Joachim Ritter:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing. **Johannes Pohl:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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